MichiganTech Research Institute

Assessing Fuel Moisture in Boreal and Arctic Ecosystems with Active and Passive Microwave Imagery

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Many Traditions One Alaska

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Natural Resources Canada

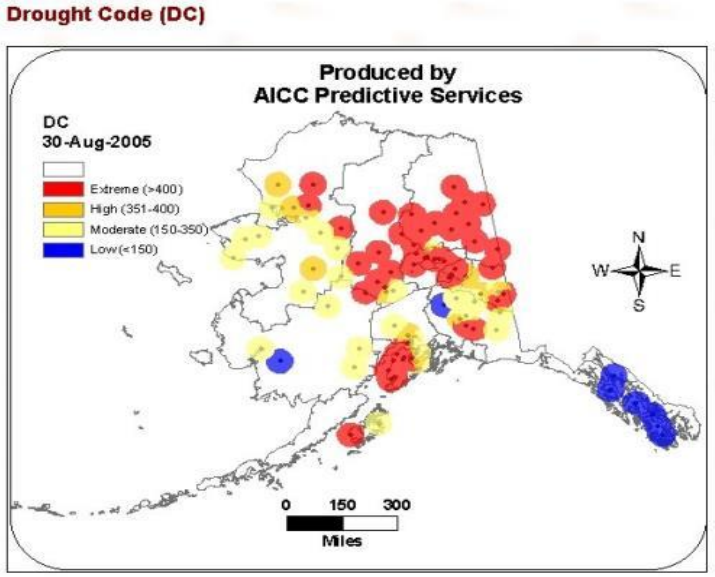
Presentation Outline

Motivation for work: improve fire danger assessment with satellite microwave imagery

- What are limitations in the current fire weather-based system for assessing fire danger?
- What is the difference in Passive and Active Microwave systems?
- What is SMAP and how may it be useful for organic layer fuel moisture assessment?
- Early results focused on assessing SMAP products for fuel moisture assessment (Compare to FWI and Fire Occurrence)
- Utility of high resolution polarimetric radar for improved high resolution organic layer fuel moisture assessment
- Summary and next steps

Introduction

- Weather based indices (e.g for CFFDRS) are invaluable for fire danger prediction
- they could be improved or augmented with high frequency repeat, satellite information. Satellite data can help by providing direct measures of organic soil moisture (FWI codes) to improve:
  - Spatial extent: i.e. areas without weather stations
  - Monitoring non-weather related changes in soil moisture (i.e. mid-summer ground thaw)
  - CFFDRS developed for more southerly boreal Canada
  - Doesn't work everywhere in the Arctic-Boreal consistently

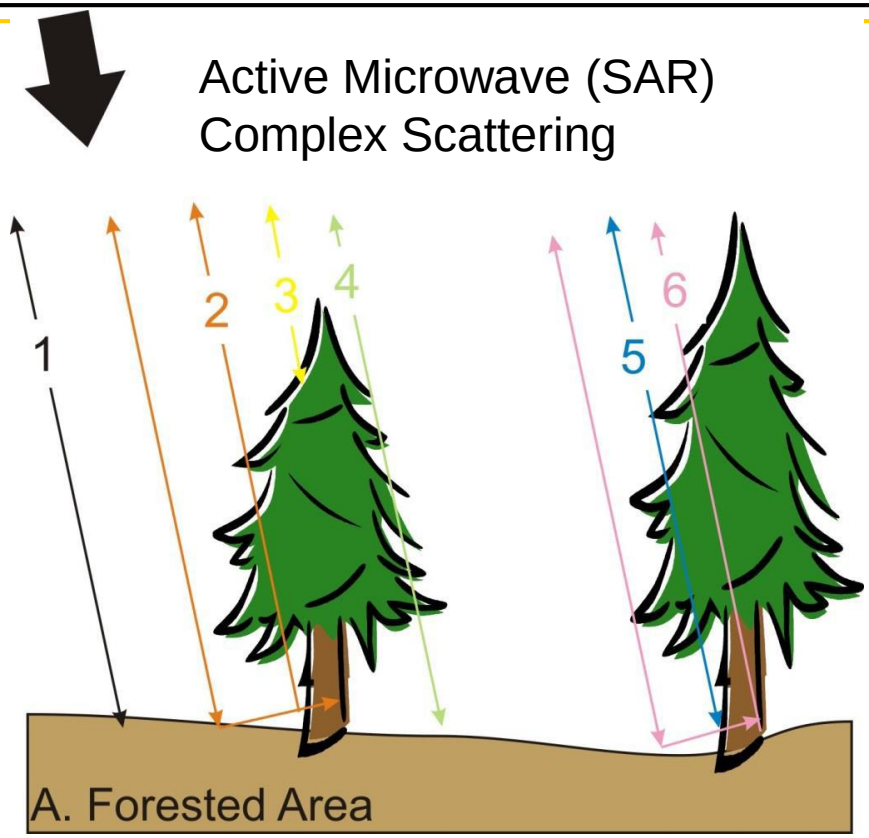


Passive vs. Active Microwave

- Objects on the Earth's surface naturally emit microwave radiation, although at relatively small energy levels.
  - Passive microwave sensors detect this naturally emitted microwave energy which is a function of the object's temperature and moisture properties.
  - Need a large field of view to record low energy → **low resolution** (example: AMSRE, SMOS, SMAP), **high repeat**
- Active microwave sensors emit their own microwave energy and record what is scattered back towards the antenna.
  - What is backscattered is a function of the image object's moisture and structure.
  - Synthetic apertures and short pulse lengths allow **high resolution** imaging. (example: Radarsat, PALSAR, Sentinel-1) – **low repeat**

Soil Moisture Retrieval from Beneath Vegetation

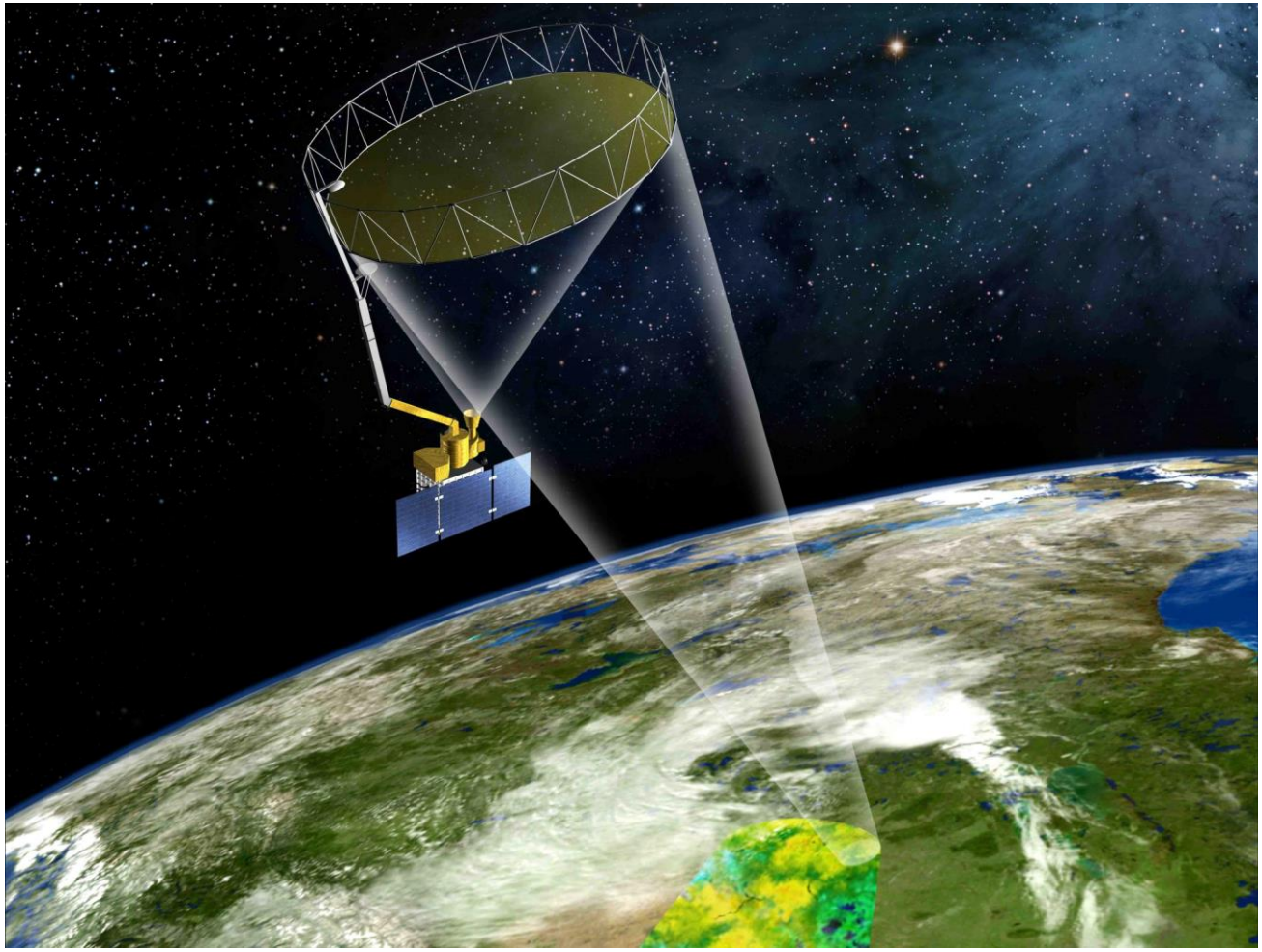
- Microwaves can penetrate vegetation canopies (depending on frequency) and provide information on the state of the soil surface.
- The strength of the microwave signal is strongly dependent on the surface soil moisture (dielectric properties) or inundation condition
- **Limititations:** Microwaves are also influenced by surface or topographic **roughness**, as well as **vegetation structure**, water content, and biomass.



Schematic diagram courtesy Chelene Krezek-Hanes CFS

Variability of vegetation structure and roughness across a landscape influences microwave retrieval of soil moisture

What is SMAP (Soil Moisture Active Passive)?



SMAP provides a capability for global mapping of soil moisture and freeze/thaw state with unprecedented coverage.

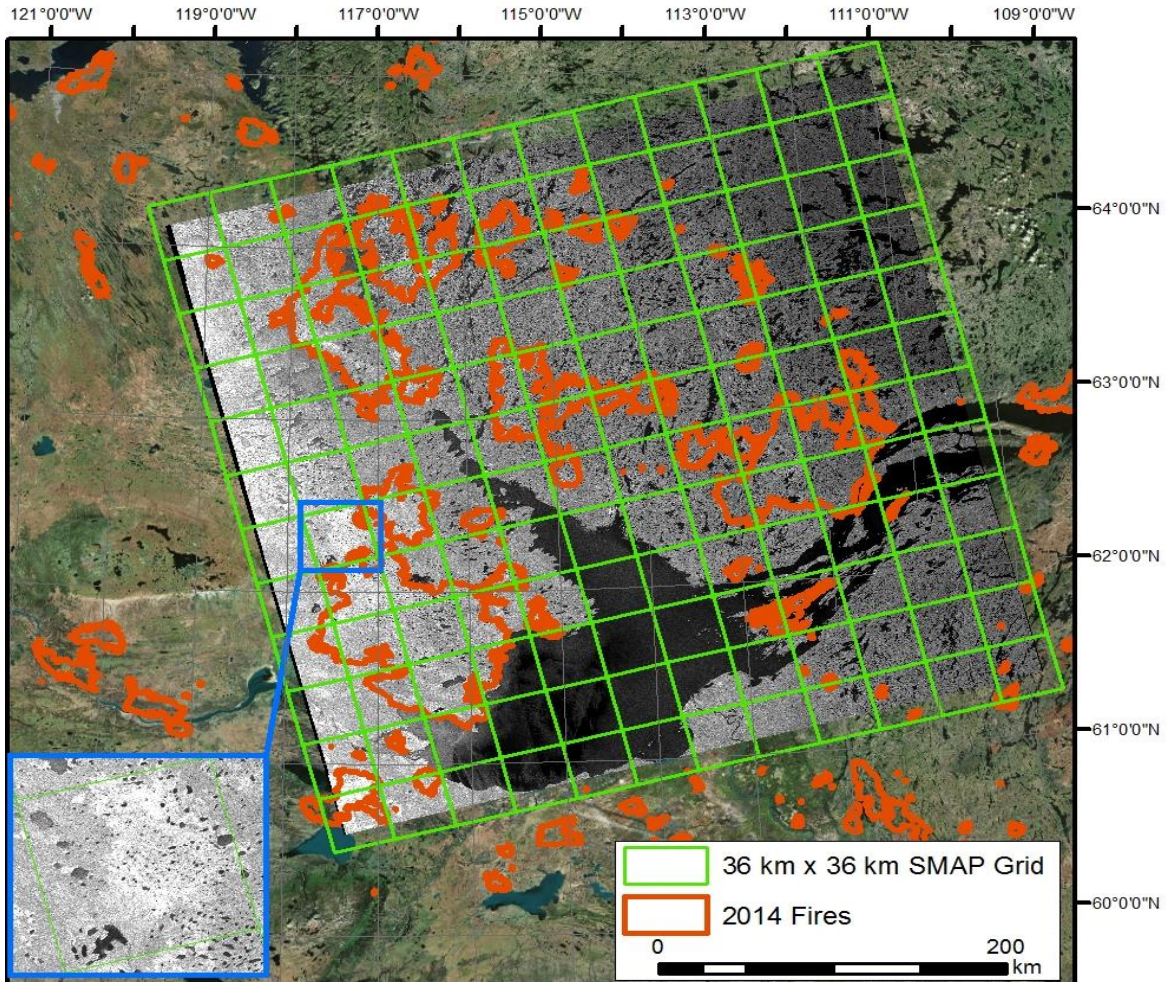
https://www.asf.alaska.edu/smap/global-impact-interactive

- NASA's L-band passive – active microwave sensors
- ~24 cm wavelength
- 2-3 day repeat
- 36 km resolution
- Global coverage
- Soil moisture products
- *Active sensor stopped working July 2015*
- *Calibration based on agricultural lands primarily- mineral soils*
- *Needs tuning to organic soils of high northern latitudes*

SMAP's Suitability for Fuel Moisture and Fire Danger Assessment in Arctic & Boreal

Key questions concerning the accuracy of SMAP products in arctic and boreal landscapes:

- does it relate to fuel moisture codes
- what depth of moisture is being sensed? 5 cm?
- spatial heterogeneity of soil moisture driven by land cover type
- calibration to organic soils
- impact of extensive surface water found in these regions



Sentinel grey scale image with 36km grid (green)

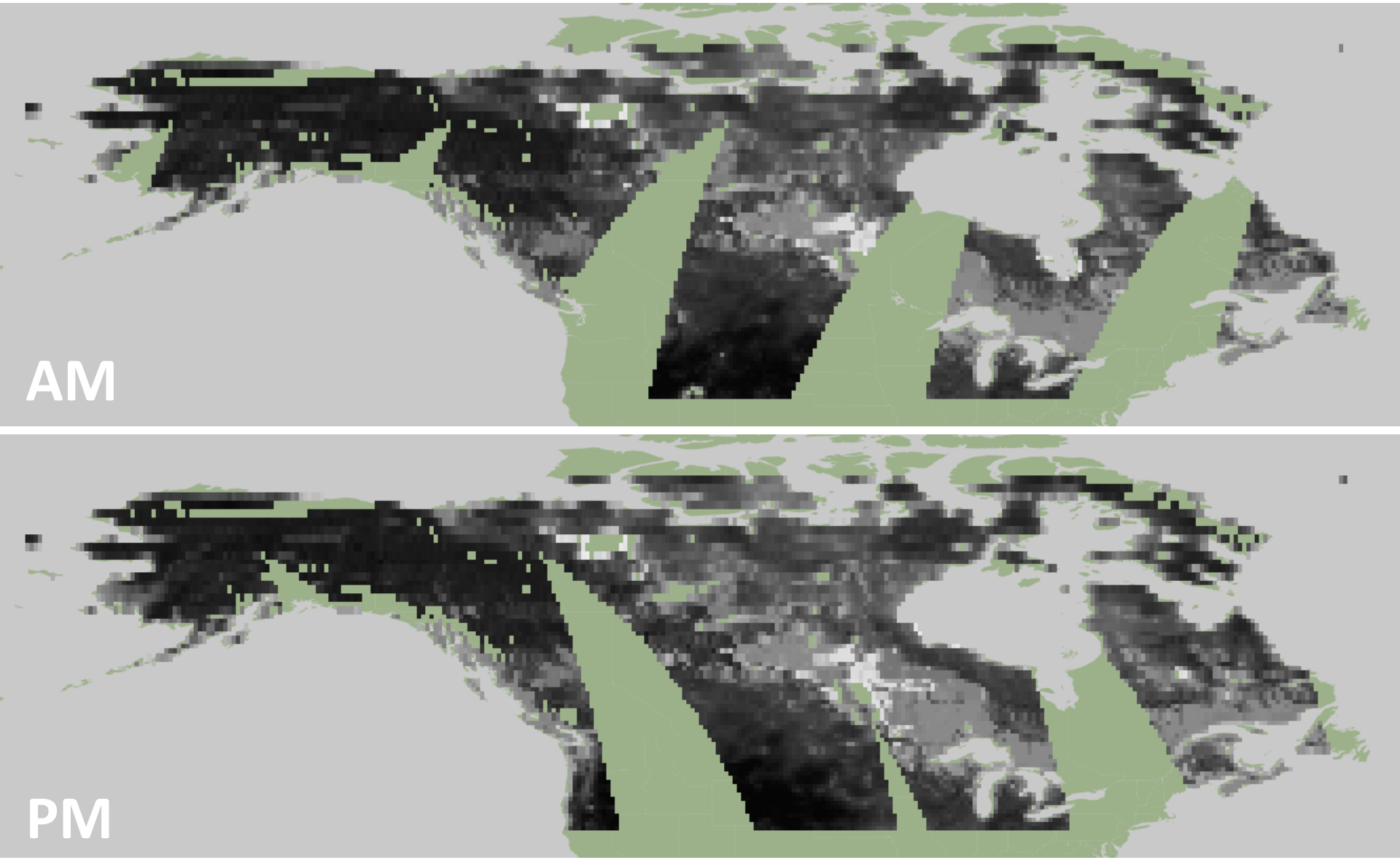
Research Objectives

1. Assess the passive microwave 36 km and new 9 km resampled product, as is, for providing 2-3 day repeat information on geospatial organic soil moisture and fire danger assessment
2. Further develop the active microwave algorithms for tundra, boreal peatland and boreal upland for both C- and L-band existing SAR satellite platforms
3. Assess whether a higher resolution product (3km) can be developed from the integration of the passive SMAP and active satellite SAR data

Obj. 1: Compare SMAP to FWI data Early Results

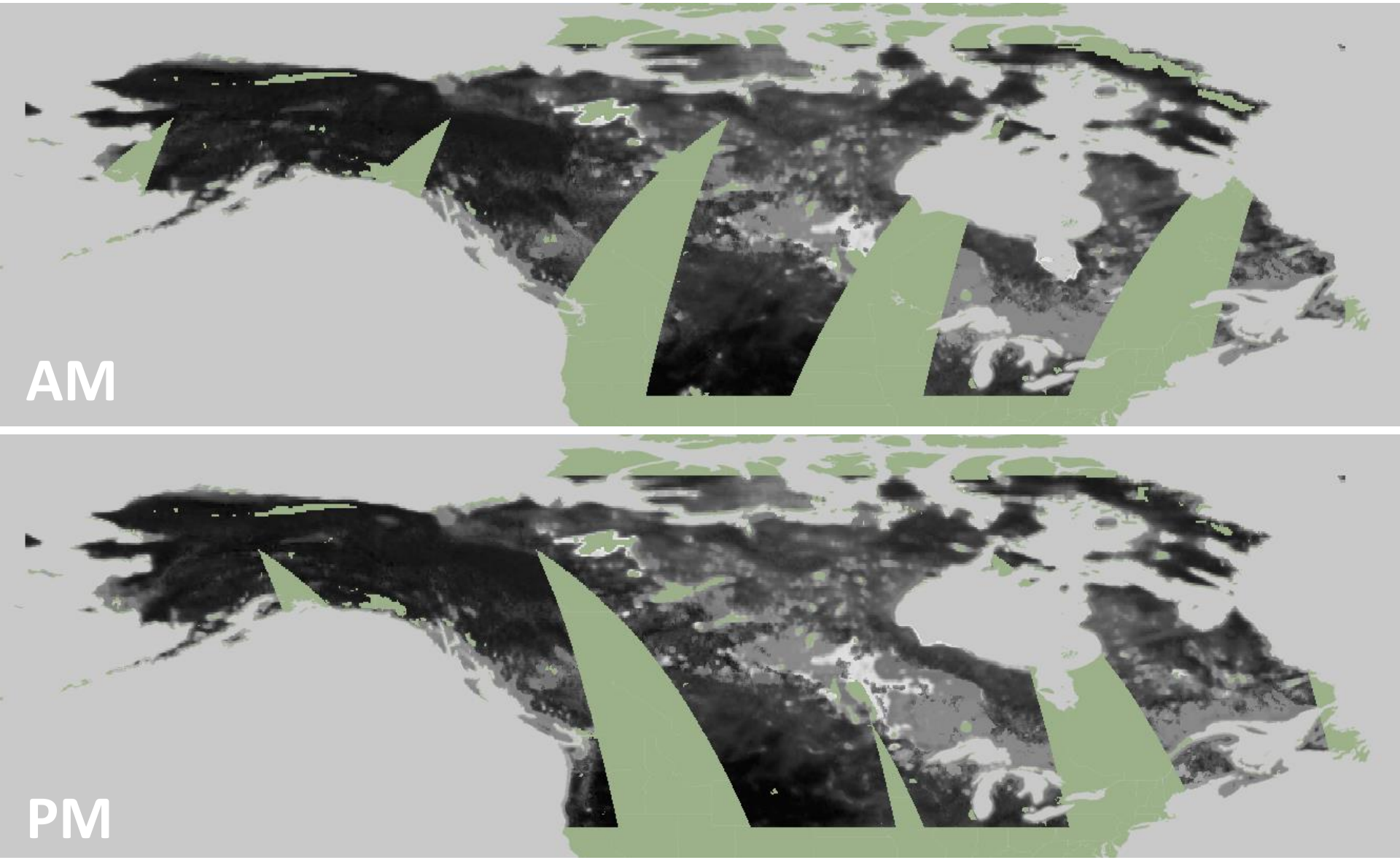
- SMAP products evaluated:
  - L3 Radiometer Global Daily 36 km Soil Moisture v4
  - *Enhanced* L3 Radiometer Global Daily 9 km Soil Moisture v1
- SMAP products were expected to correlate best with the FWI fuel codes representative of the near surface moisture conditions (e.g. FFMC or DMC).

Obj. 1: Compare SMAP to FWI data



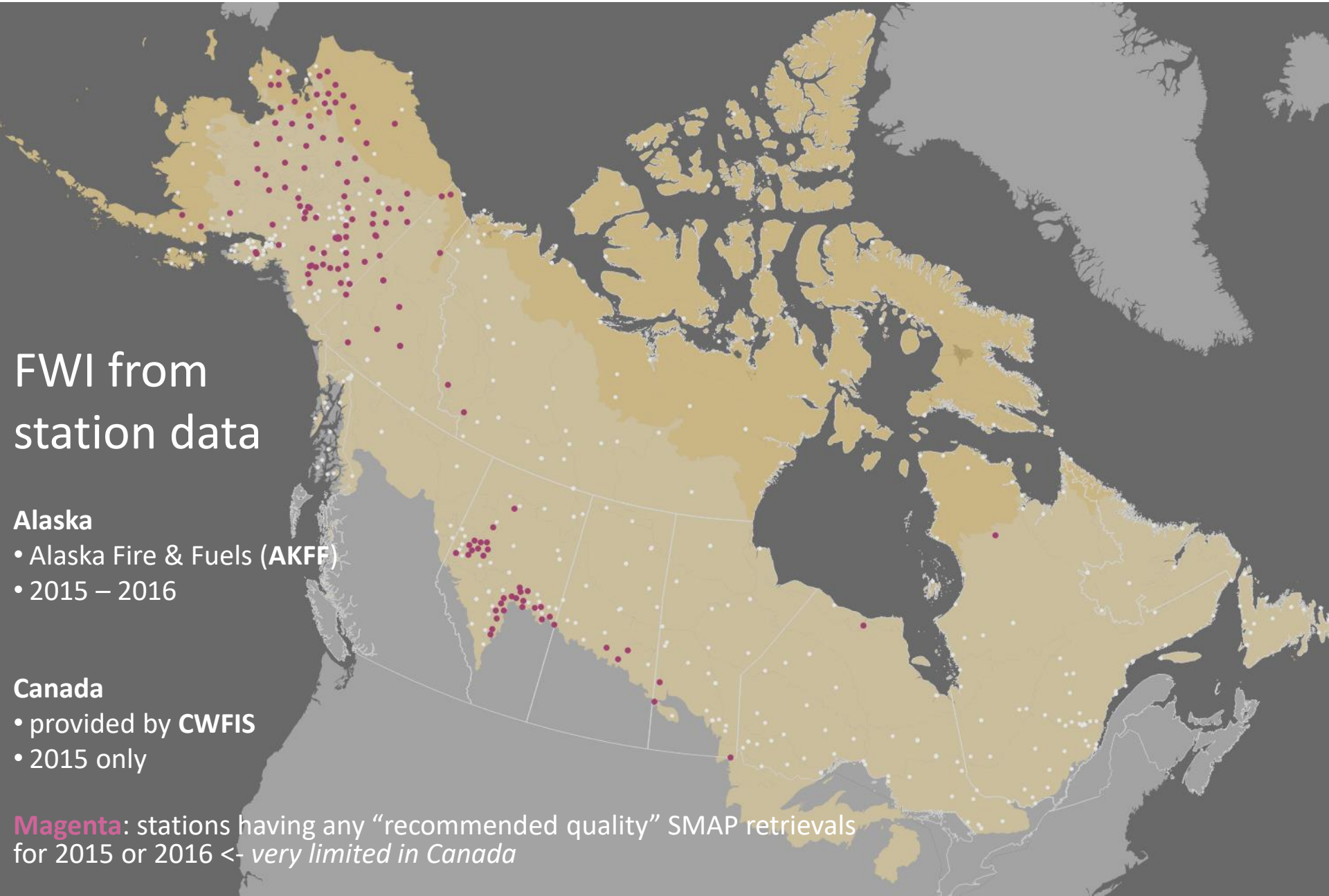
SMAP L3 **36 km** soil moisture, Sept 9 2015

Obj. 1: Compare SMAP to FWI data



SMAP L3 **9 km** soil moisture, Sept 9 2015

Obj. 1: Compare SMAP to FWI data



FWI from station data

Alaska
- Alaska Fire & Fuels (**AKFF**)
- 2015 – 2016

Canada
- provided by **CWFIS**
- 2015 only

Magenta: stations having any “recommended quality” SMAP retrievals for 2015 or 2016 <- *very limited in Canada*

Obj. 1 Results Comparing SMAP to FWI

- Used multivariate General Additive Modeling to predict FWI indices from SMAP soil moisture retrievals:

FWI index	R^2 of best-fit model
BUI	0.53
DC	0.62
DMC	0.52
FFMC	0.18
FWI	0.31
ISI	0.16

Obj. 1: SMAP DC-prediction Model

DC = soil_moisture + elevation + s(day-of-year)* + te(longitude,latitude)*

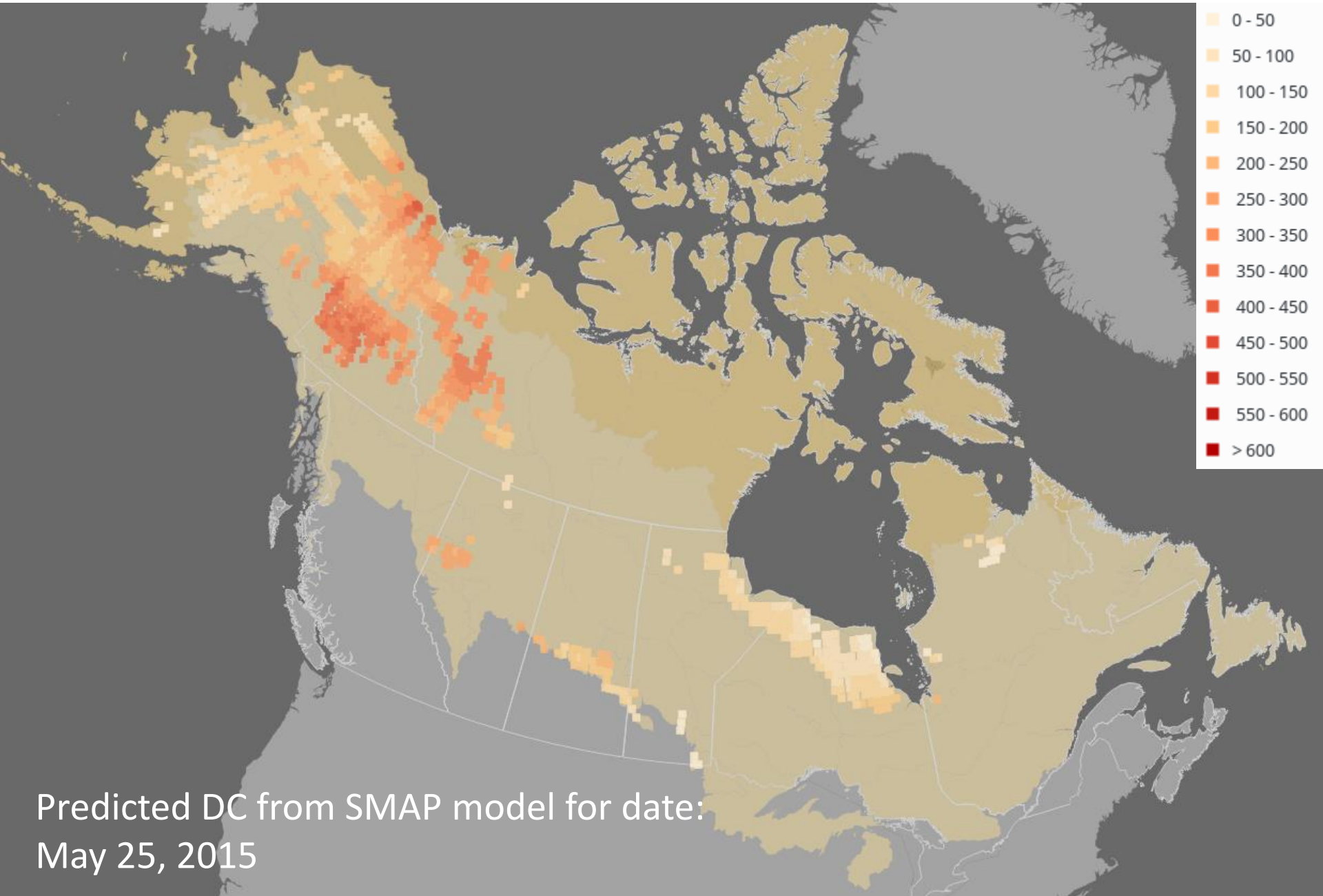
*Non-parametric terms

*Adjusted R^2= 0.**62***

- Data subset:
  - Both AM and PM retrievals; averaged when both were “recommended quality”
  - day-of-year > 145 (~May 25)
  - day-of-year < 288 (~Oct 15)
  - AK: ‘15-’16; CA: ‘15 only
- Statistical model: Generalized Additive Model (can include non-parametric relationships)

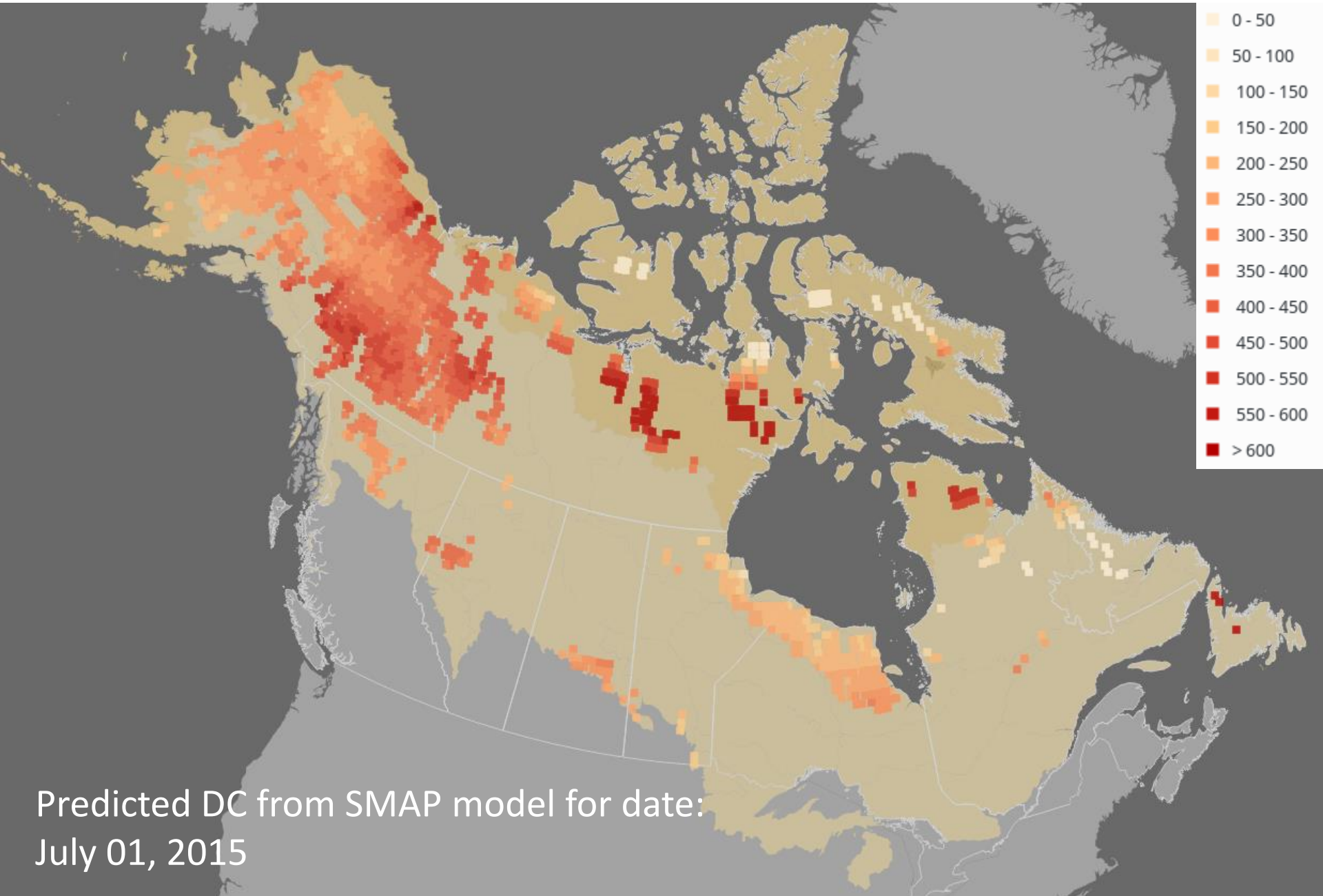
- Parameters tested but excluded:
  - IGBP landcover, albedo, incidence angle, static_water_body_fraction, roughness

Obj. 1: SMAP-Derived Drought Code



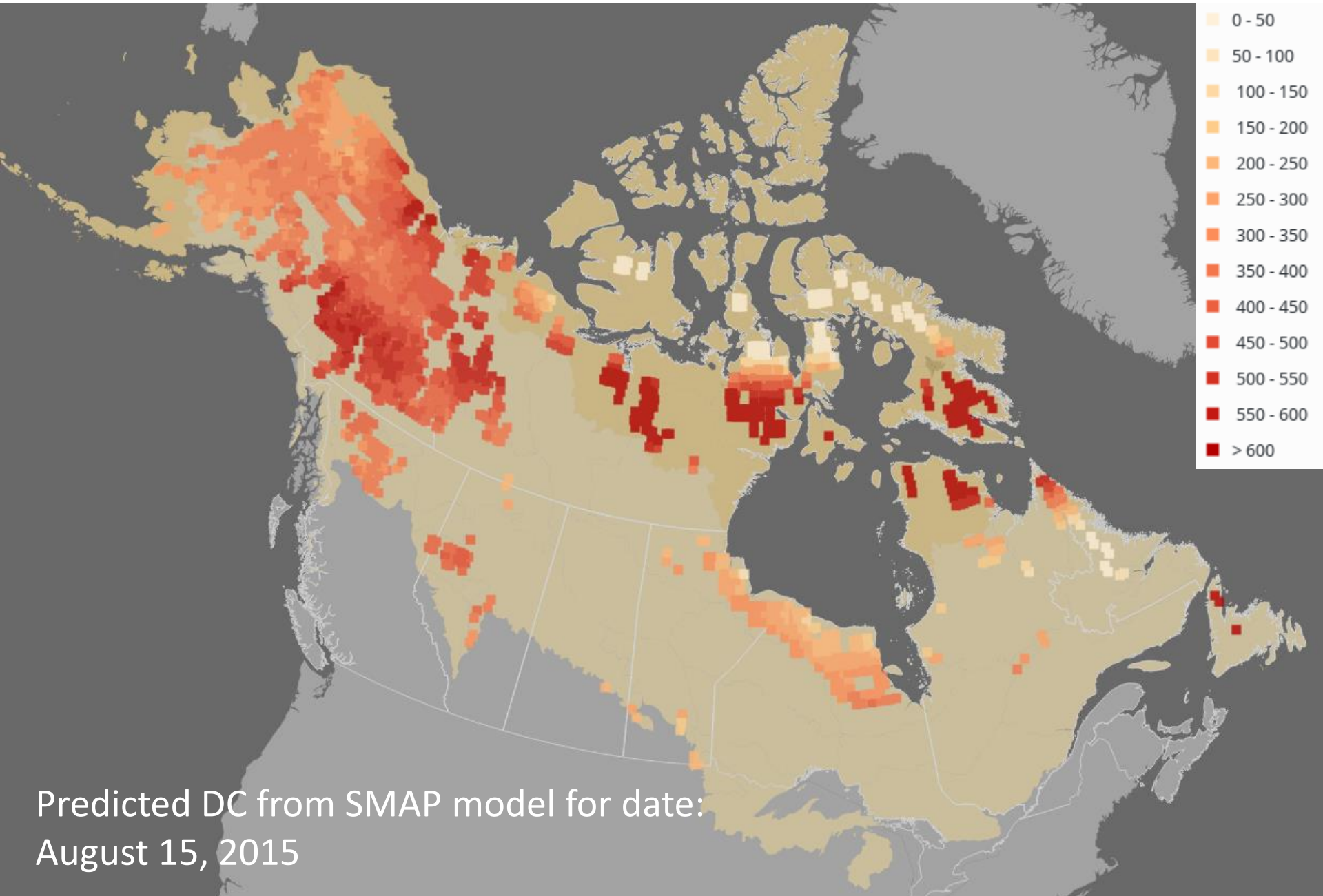
Predicted DC from SMAP model for date:
May 25, 2015

Obj. 1: SMAP-Derived Drought Code

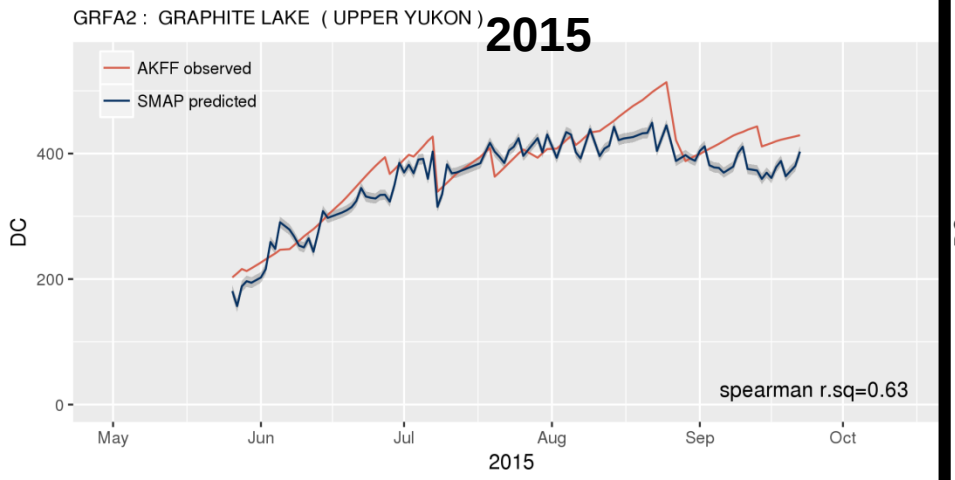


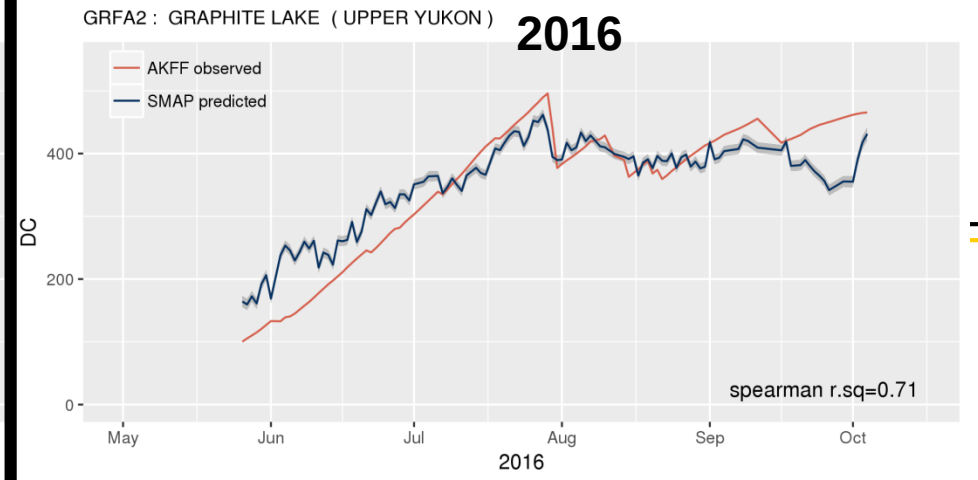
Predicted DC from SMAP model for date:
July 01, 2015

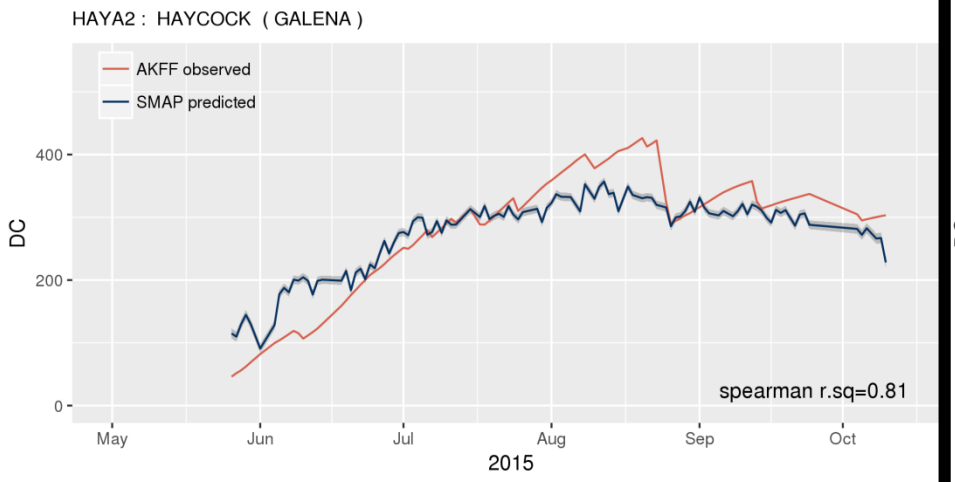
Obj. 1: SMAP-Derived Drought Code

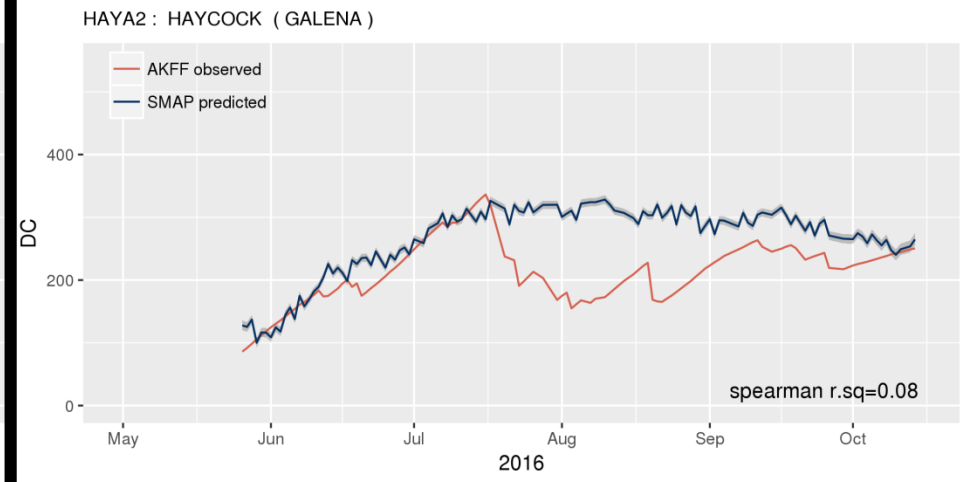


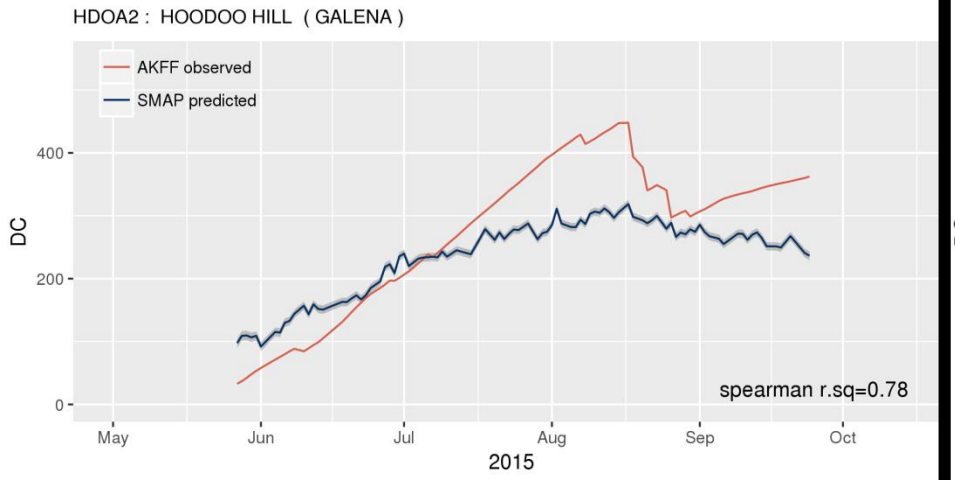
Predicted DC from SMAP model for date:
August 15, 2015

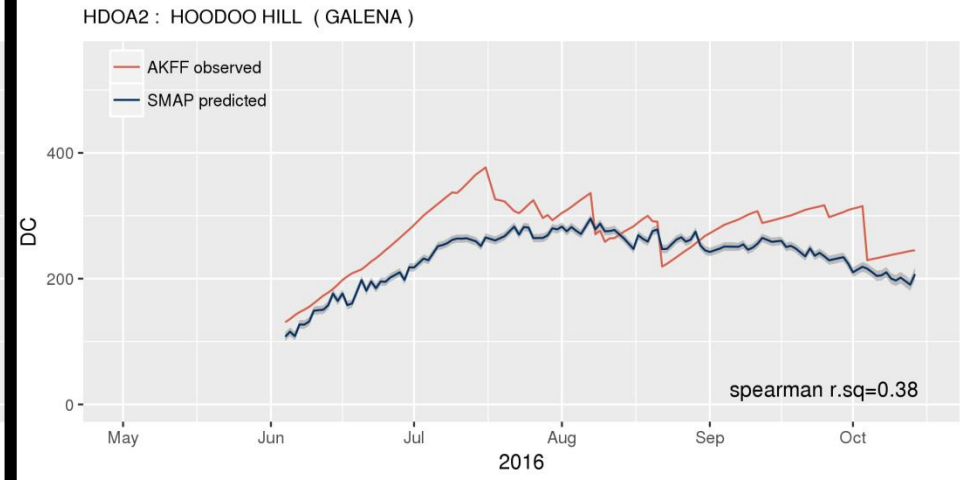

GRFA2 : GRAPHITE LAKE (UPPER YUKON)
2015
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.63

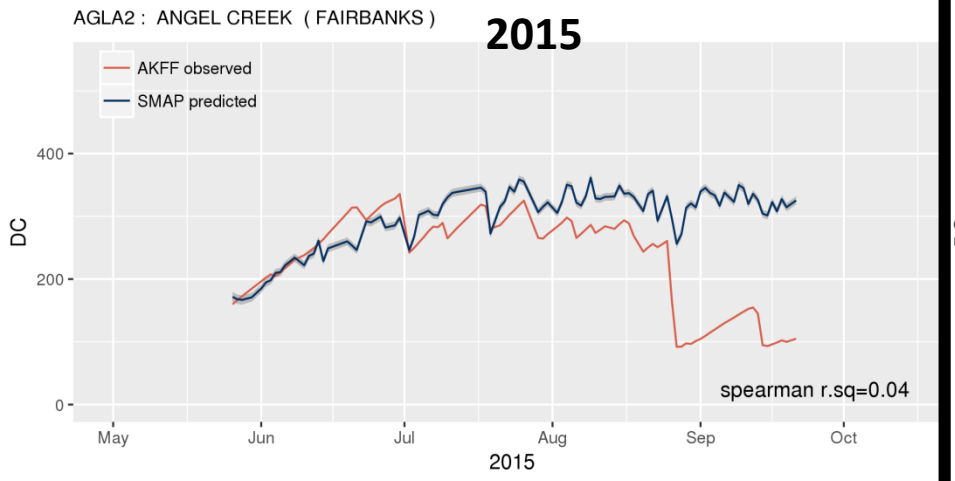

GRFA2 : GRAPHITE LAKE (UPPER YUKON)
2016
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.71

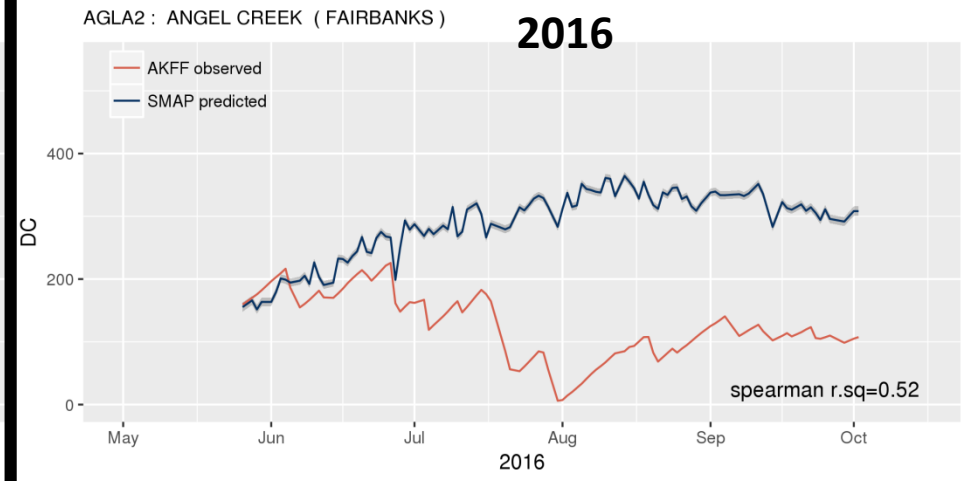

HAYA2 : HAYCOCK (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.81

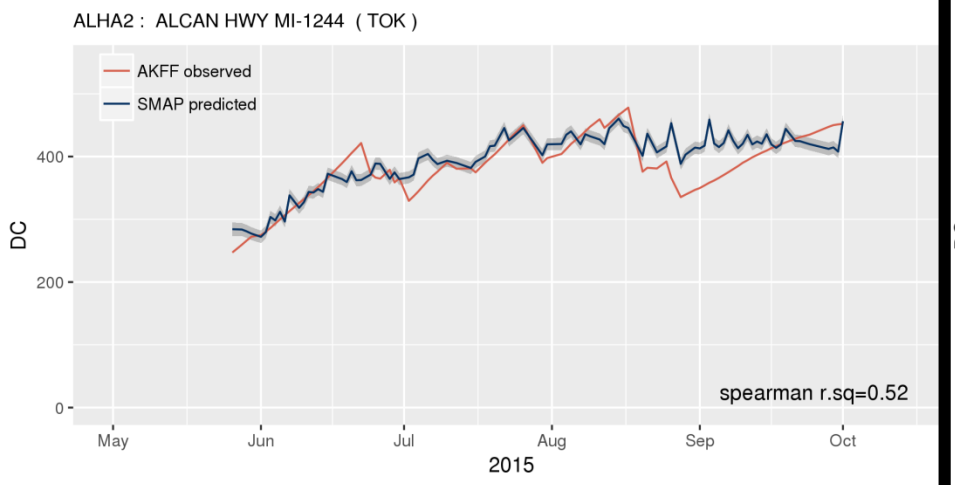

HAYA2 : HAYCOCK (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.08

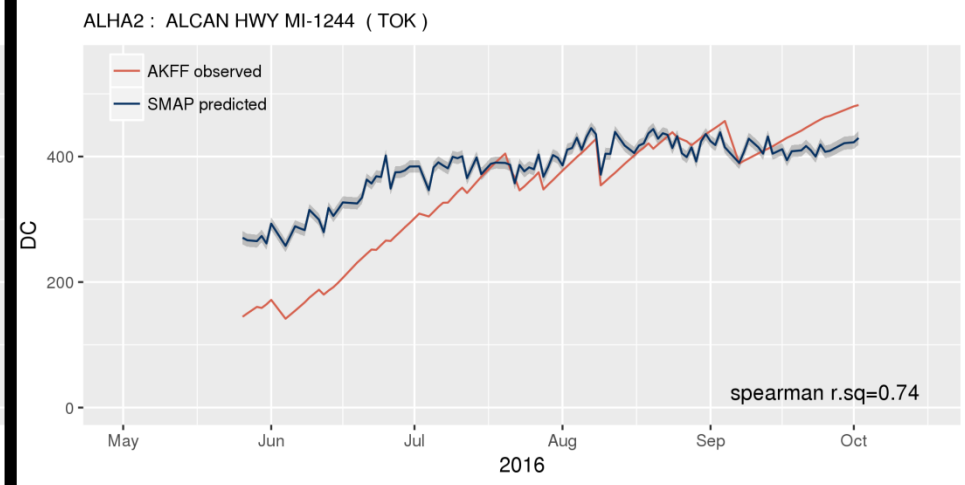

HDOA2 : HOODOO HILL (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.78

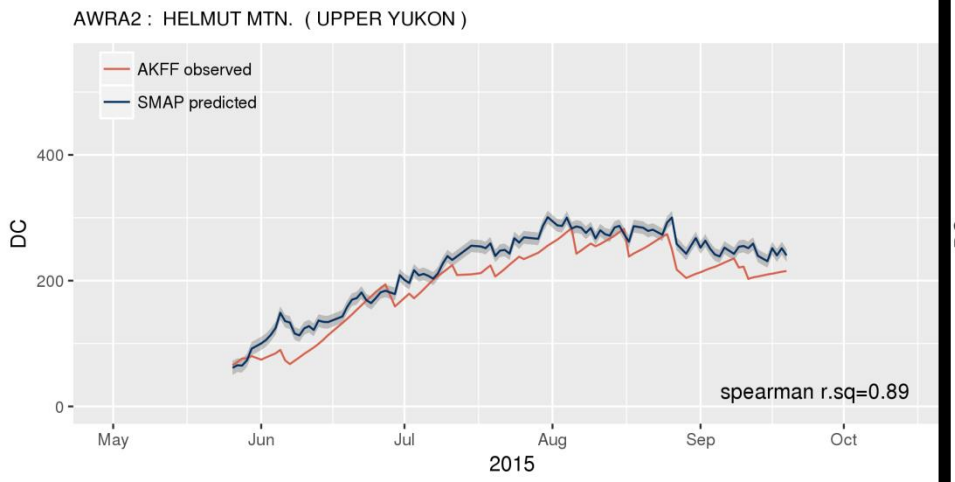

HDOA2 : HOODOO HILL (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.38

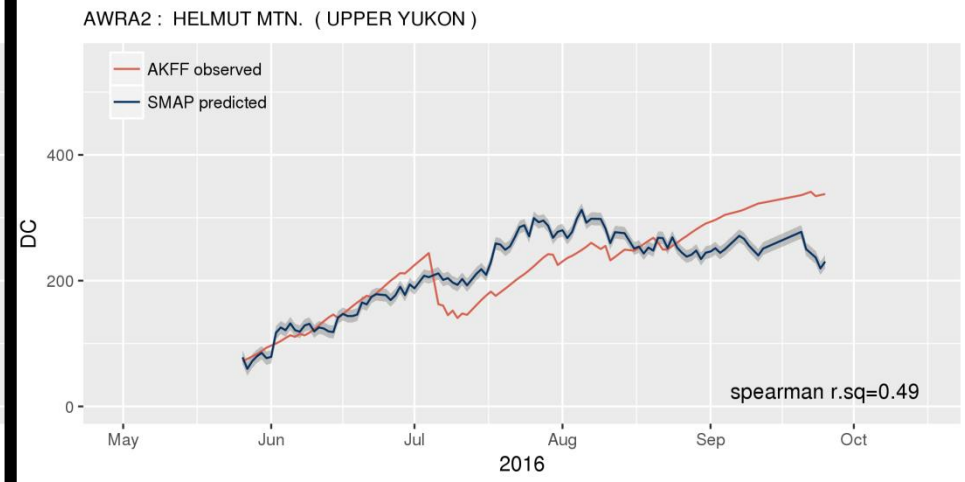

AGLA2 : ANGEL CREEK (FAIRBANKS)
2015
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.04


AGLA2 : ANGEL CREEK (FAIRBANKS)
2016
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.52


ALHA2 : ALCAN HWY MI-1244 (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.52

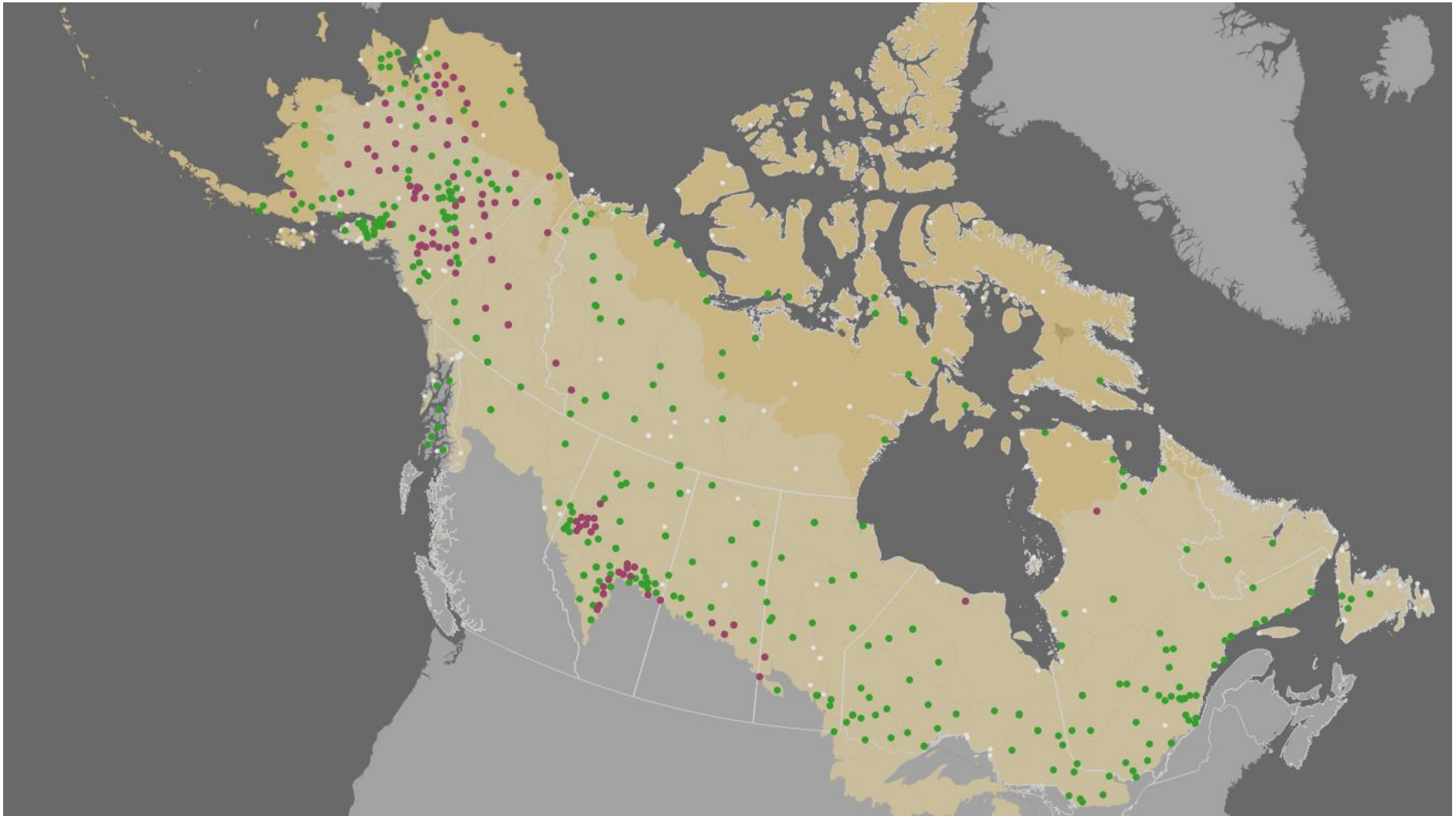

ALHA2 : ALCAN HWY MI-1244 (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.74


AWRA2 : HELMUT MTN. (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.89


AWRA2 : HELMUT MTN. (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.49

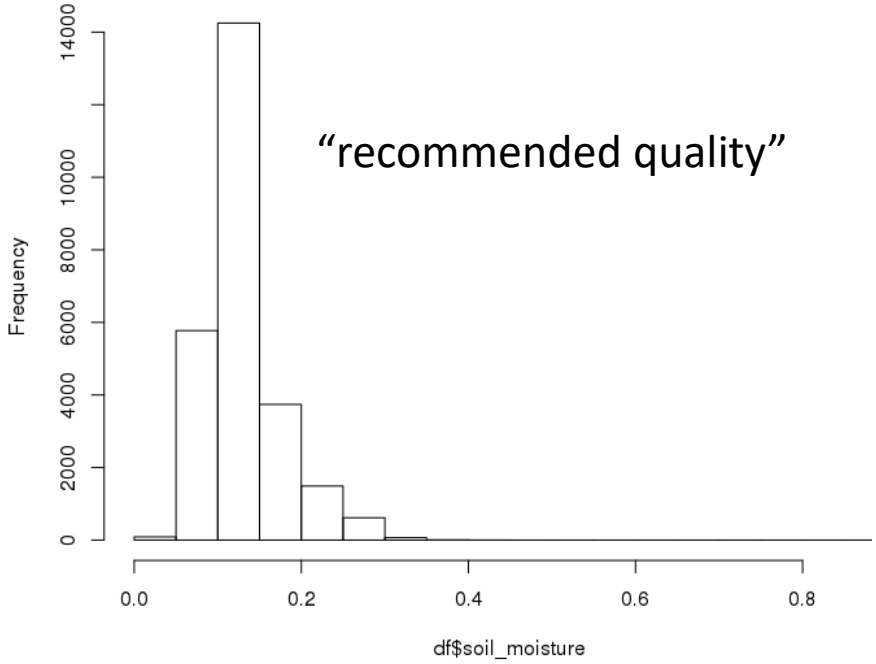
Obj. 1: Compare SMAP to FWI data – include all stations

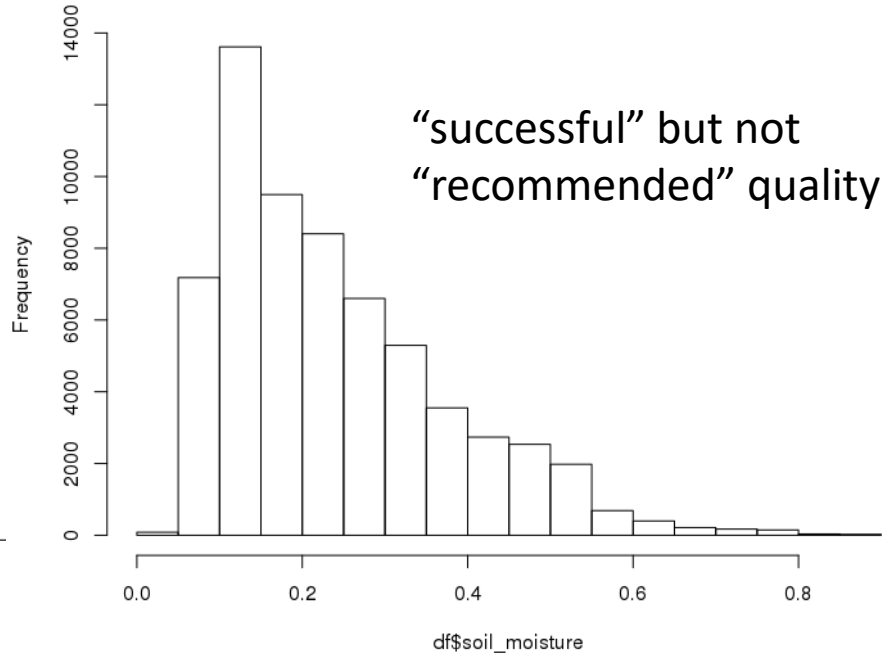
- To get better network coverage in Canada, what happens if we include some of the lesser quality SMAP retrievals?
  - Below: **green** stations are added if we include lesser quality retrievals



Obj. 1: Compare SMAP to FWI data

- To get better network coverage in Canada, what happens if we include some of the lesser quality SMAP retrievals?
  - Soil moisture value distribution:



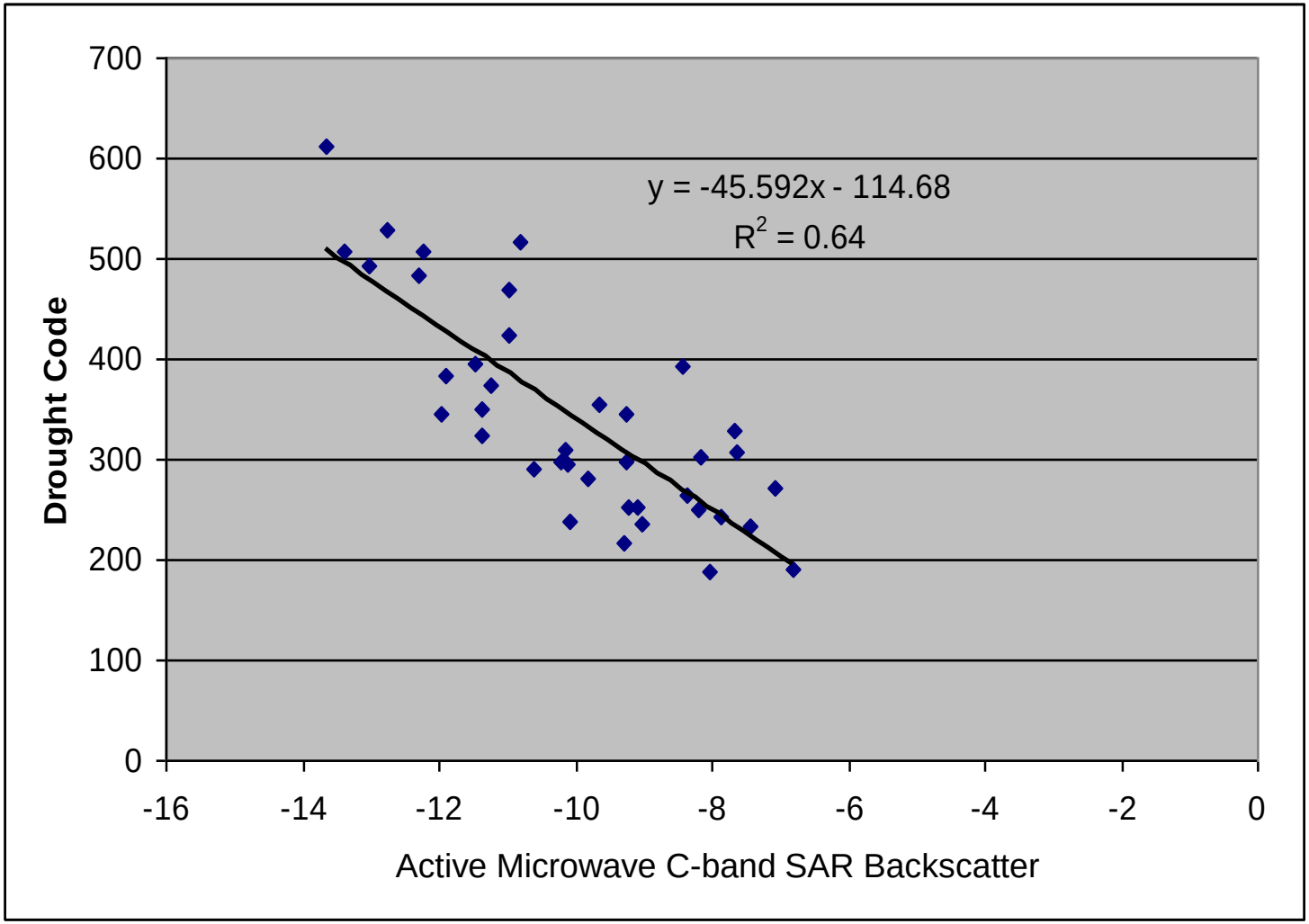


  - DC model performance:
    - Adj. R^2 drops from 0.**62** to 0.**58**

Obj. 2: Further Develop Active Microwave Algorithms for C- and L-band

- Build from Single Channel SAR algorithms – 1 variable predictor
- Develop improved satellite SAR moisture retrieval algorithms using polarimetric data (multiple variable predictor) to account for effects of biomass and surface roughness on the SAR signal for:
  - Boreal Uplands
  - Boreal Peatlands
  - Tundra

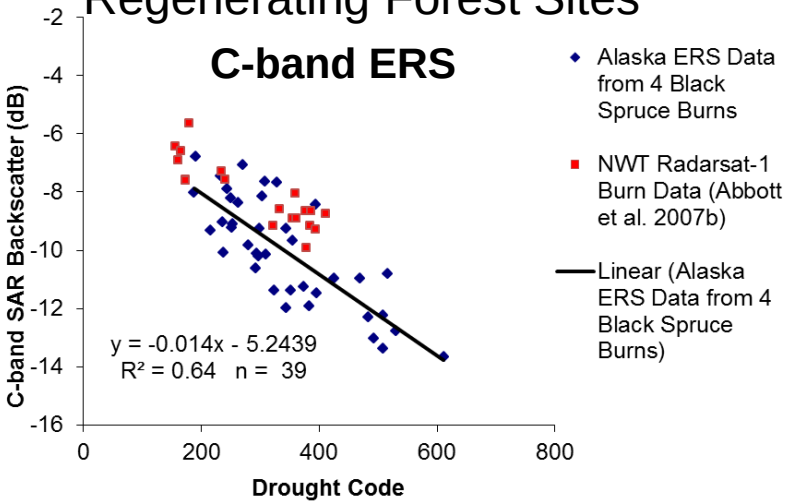
Obj. 2: Early Active Microwave DC Prediction Algorithms from Single Channel C-band From Regenerating Forests



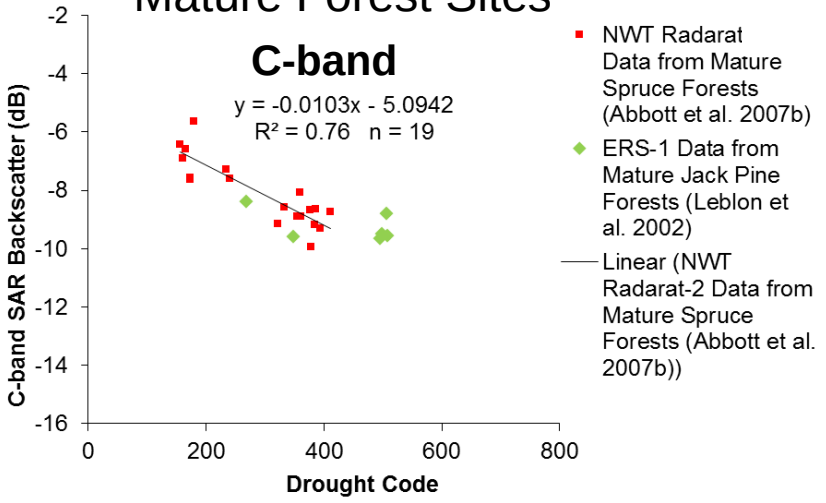
Bourgeau-Chavez et al. 1999 IJWF, 2007 Polar Record

Obj. 2 Active Microwave Algorithms for Single Channel C- and L-band DC and Moisture Retrieval

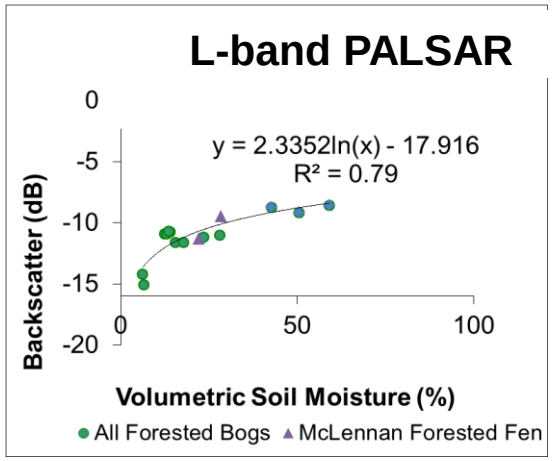
Regenerating Forest Sites



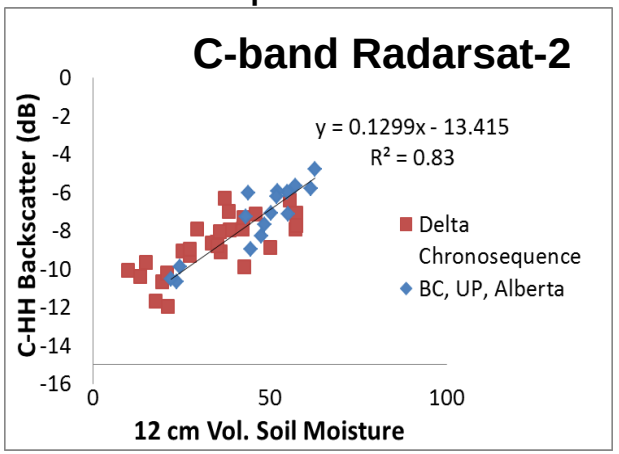
Mature Forest Sites



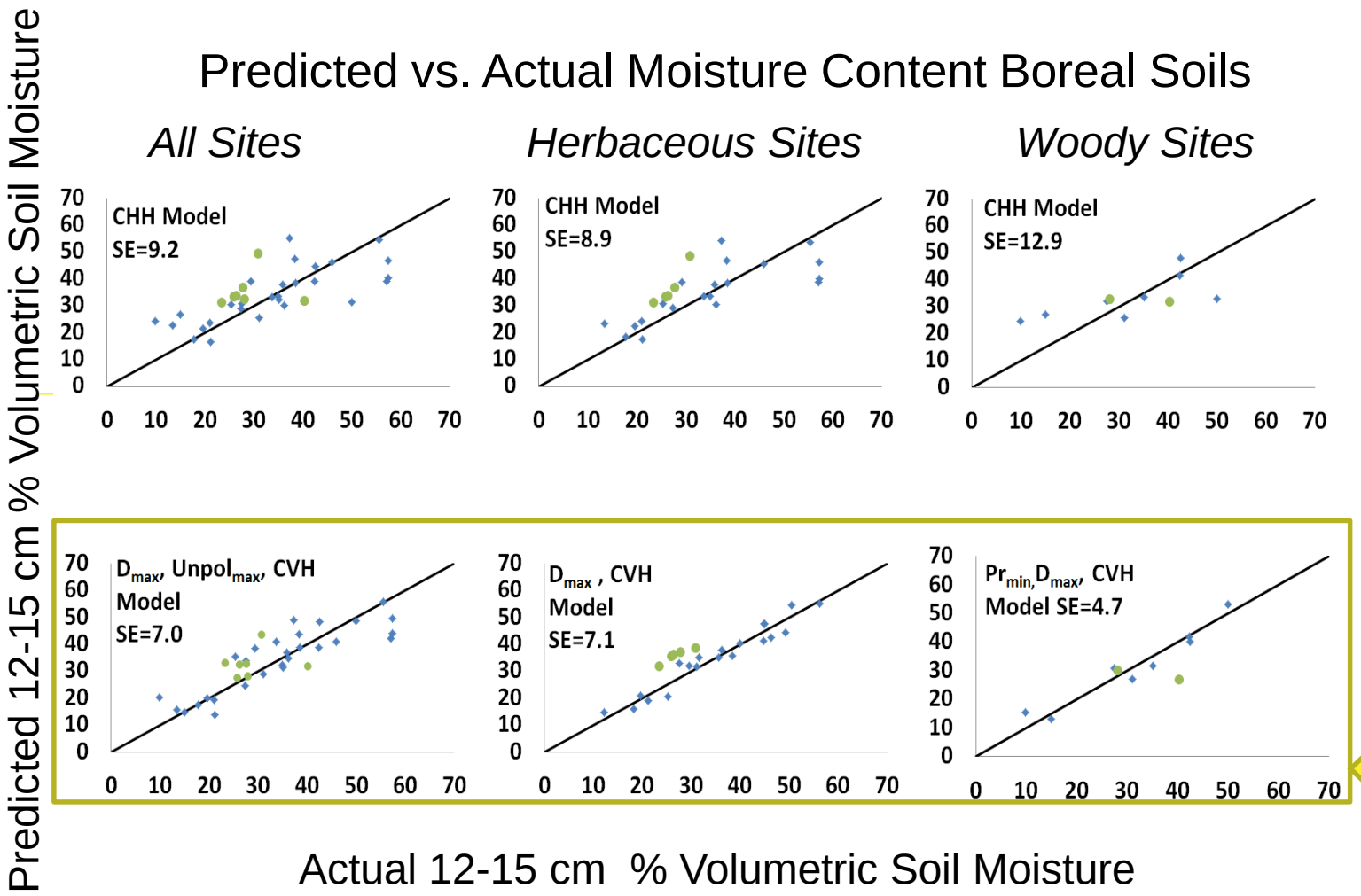
Forested Peatland Sites



Peatland and Regenerating Black Spruce Sites



Obj. 2 Further Develop Active Microwave Algorithms C-band Polarimetry - Uplands



Boreal Ecosystems Show 27-33% improvement in retrieval accuracy with Polarimetric SAR over traditional single channel CHH model and four polarization SAR backscatter capability.

Bourgeau-Chavez et al. 2013 Rem Sens Environment

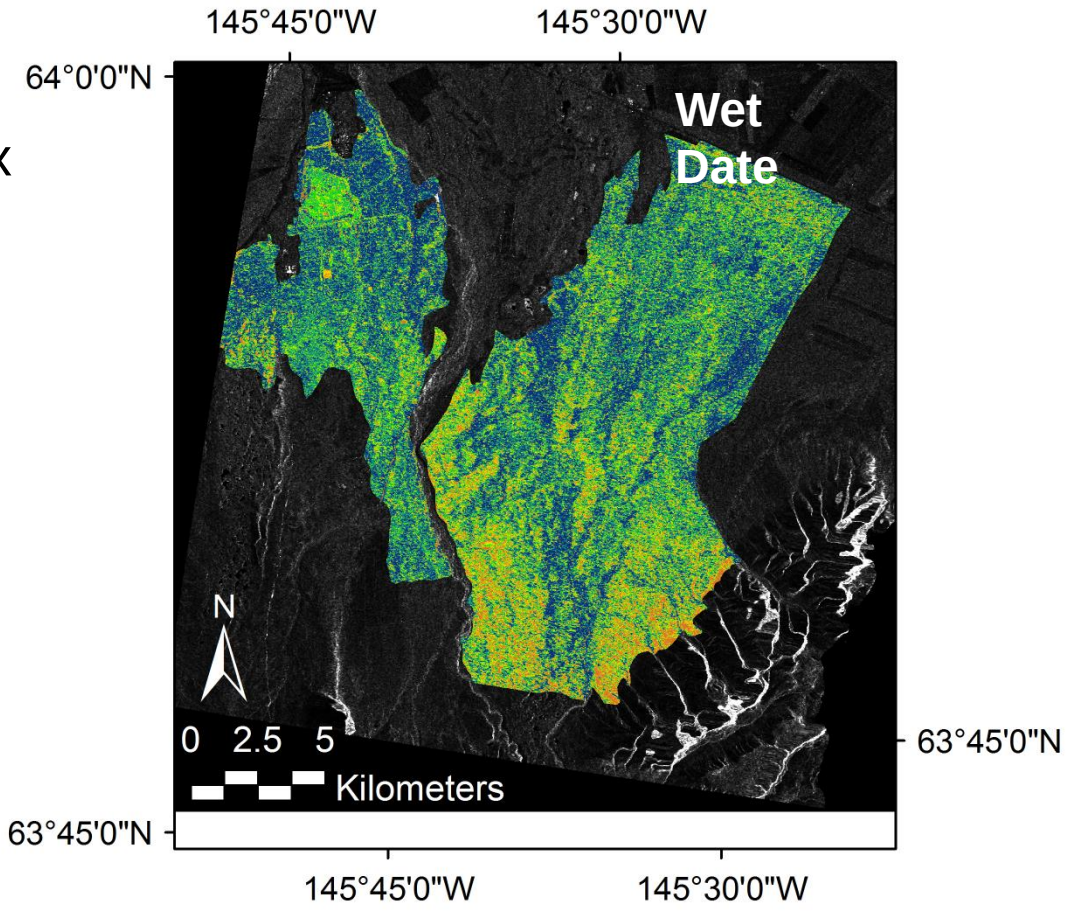
Obj. 2 Polarimetric C-band SAR-Derived Soil Moisture Maps: *Boreal Alaska Site*

Combining variables that appear strongly correlated to the structural complexity (max degree polarization) with variables strongly related to soil moisture (CHH, CVV, CVH) improved empirical algorithms by 27-33%

R^2 = 0.77, Accuracy = 6.7% volumetric moisture content (RMSE).

Note: Mature forest areas (> 1.7 kg/m^2 biomass) are removed from maps.

More research is needed to extend the models to L-band and greater biomass areas



Predictive Algorithm for All Sites:

%VMC = 319.31 D_{max} -612.50 $Unpol_{max}$ + 5190.4 C-VH -266.37

Bourgeau-Chavez et al. 2013 Rem Sens Environment

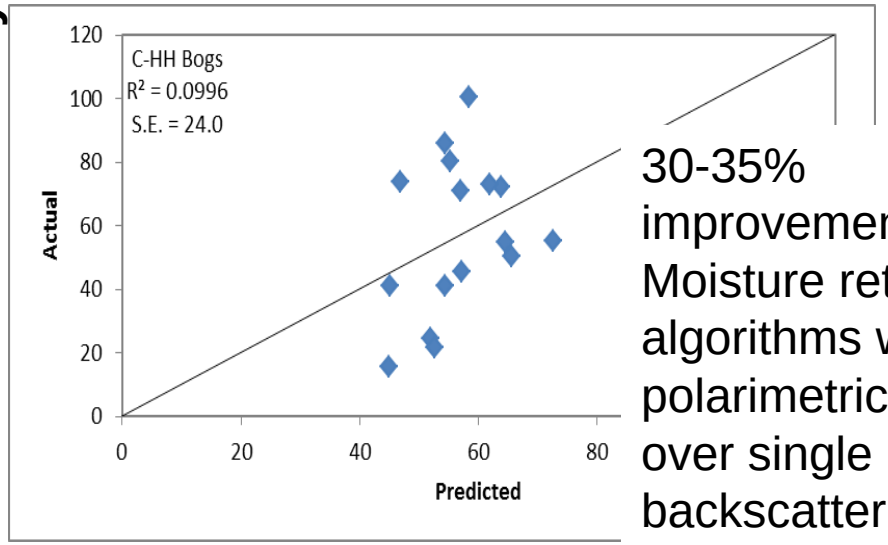
C-band SAR Peatland Organic Soil Moisture Algorithms

Predicted vs. Actual Plots

All Bogs

All Fens

SAR Backscatter only



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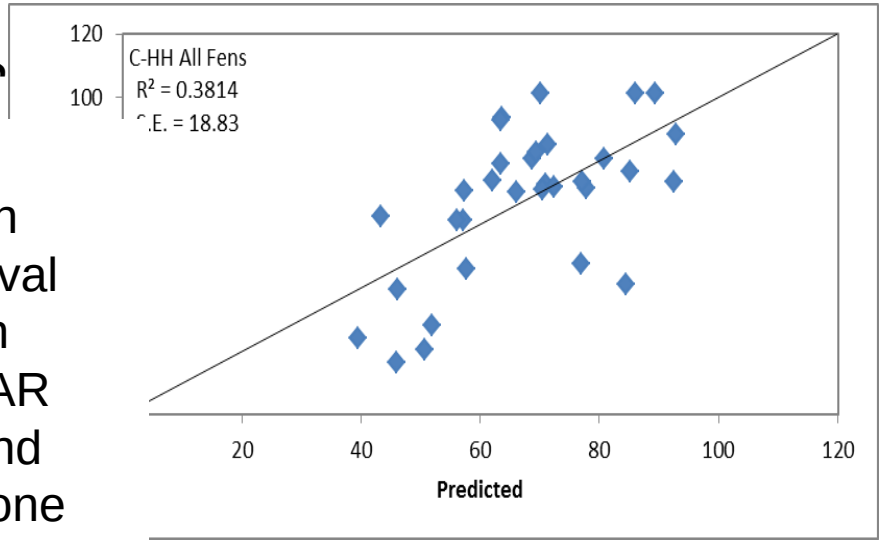
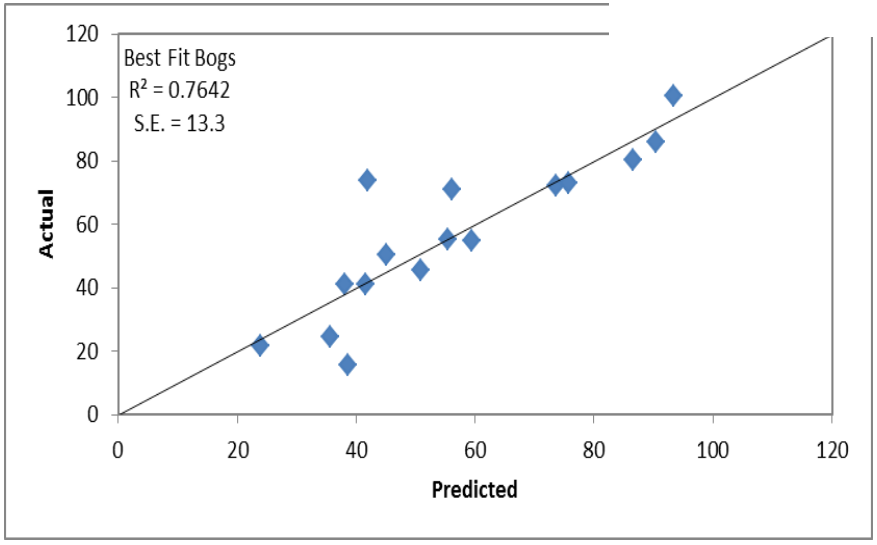
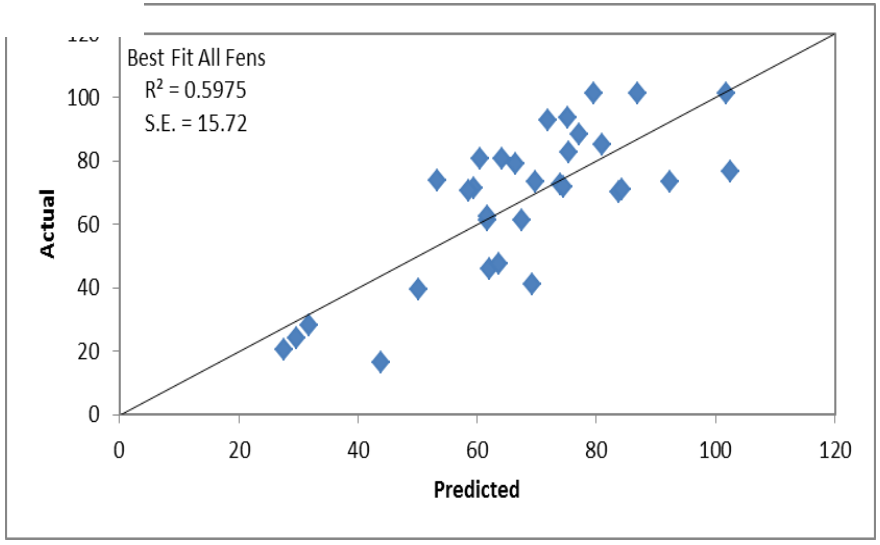


30-35% improvement in Moisture retrieval algorithms with polarimetric SAR over single band backscatter alone

Polarimetric SAR

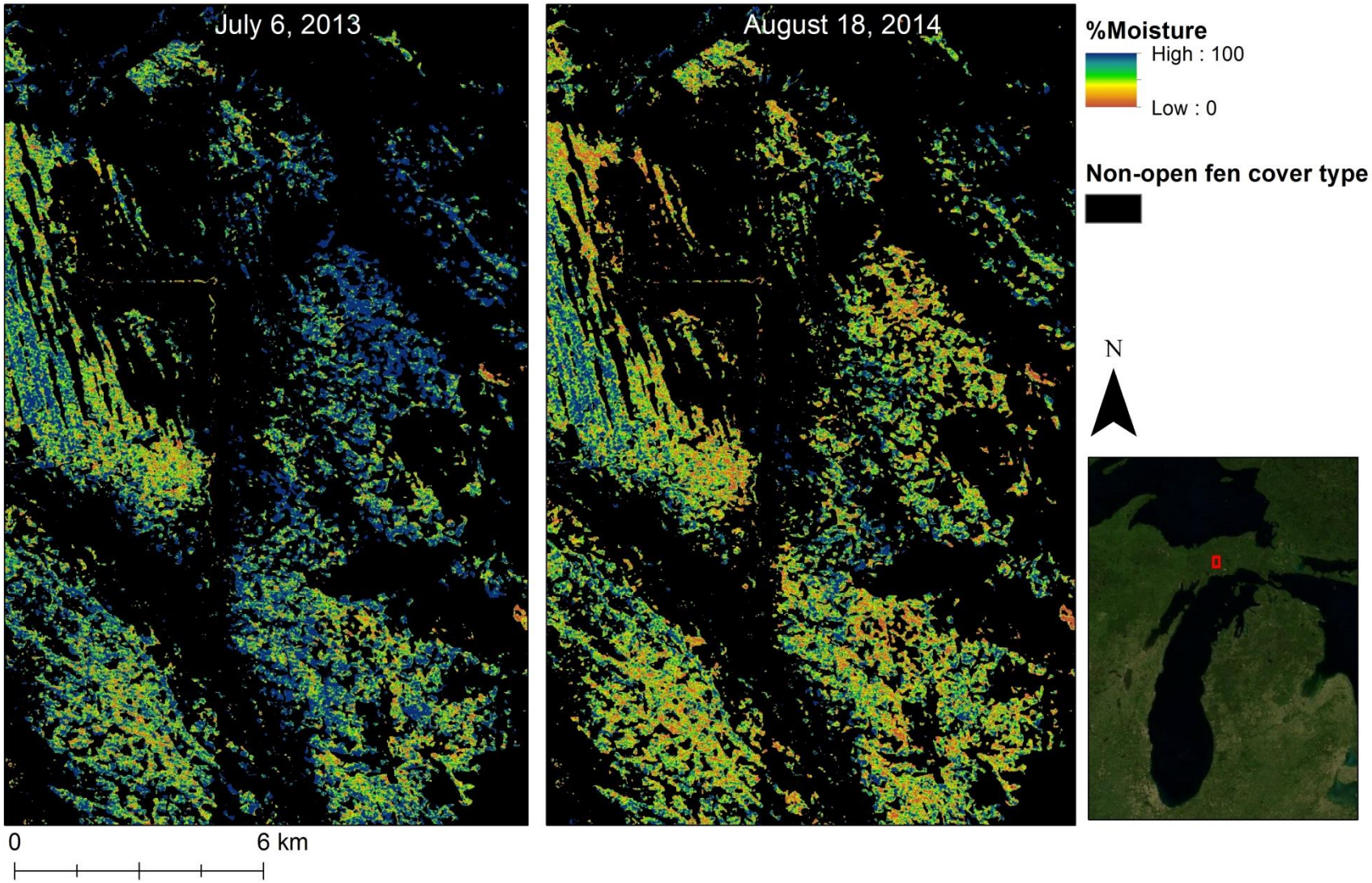


Polarimetric SAR



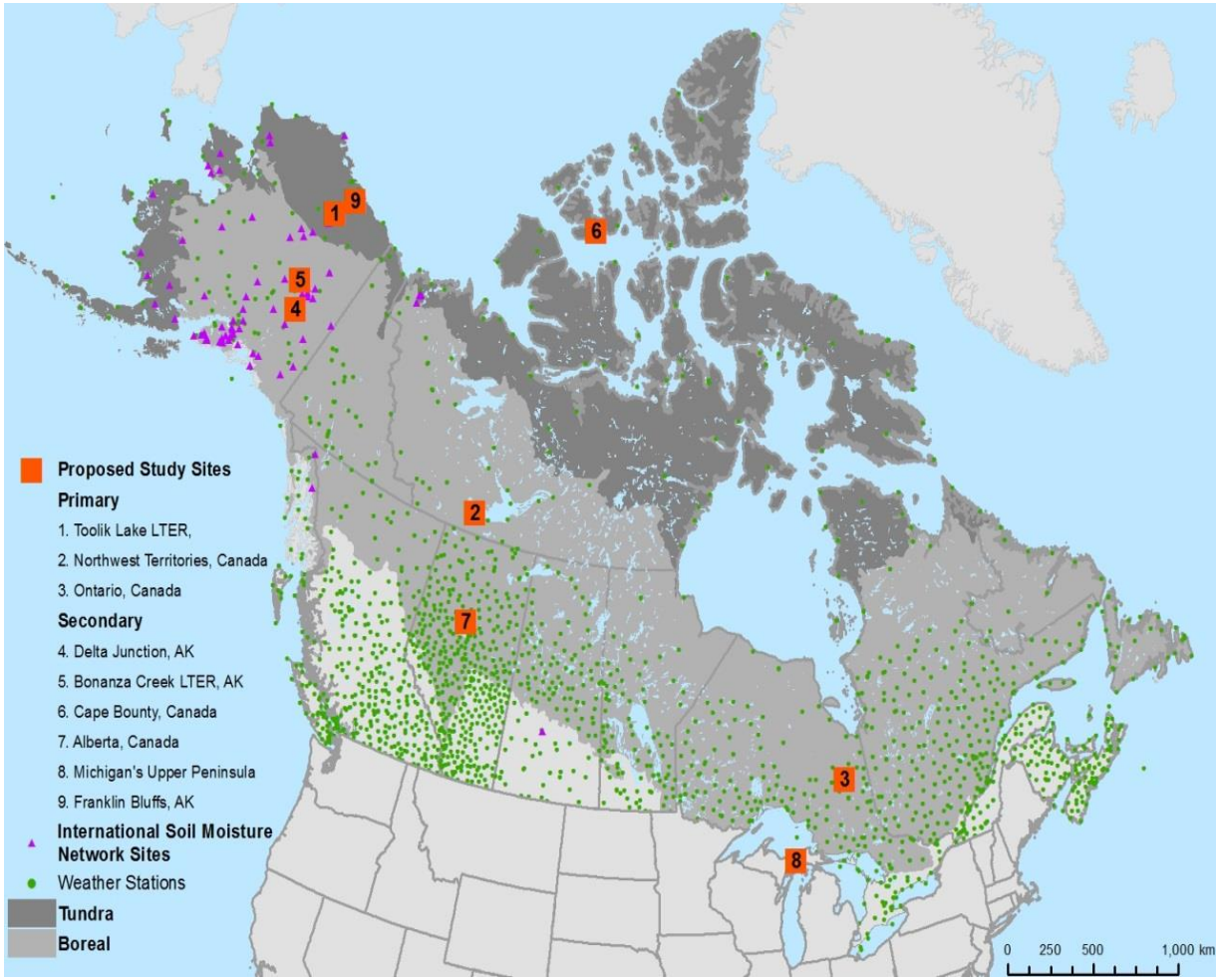
Radarsat-2 Peatland Moisture Maps

Seney Open Fens on a Wet and Dry date



Obj. 2: *Further* Develop Active Microwave Algorithms for C- and L-band SARs

- Red boxes are primary study sites for Obj. 2. Most are collaborative studies
- The (1) Tundra site, (2) Boreal Peatland and (3) Boreal Upland sites will be instrumented this spring
- Magenta dots have soil moisture and green dots have weather data available for addressing

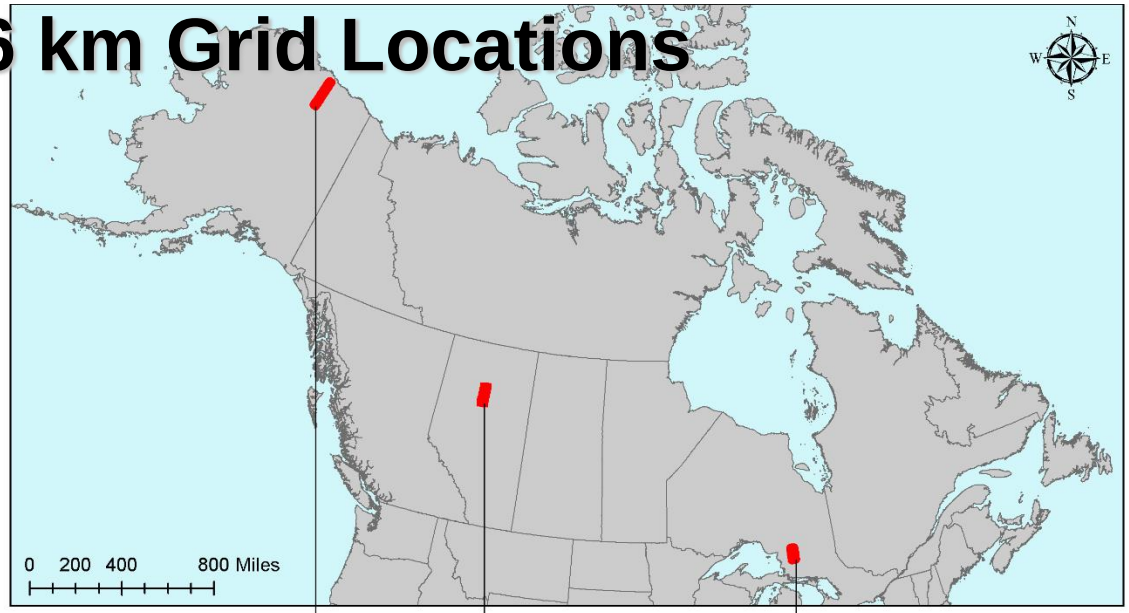


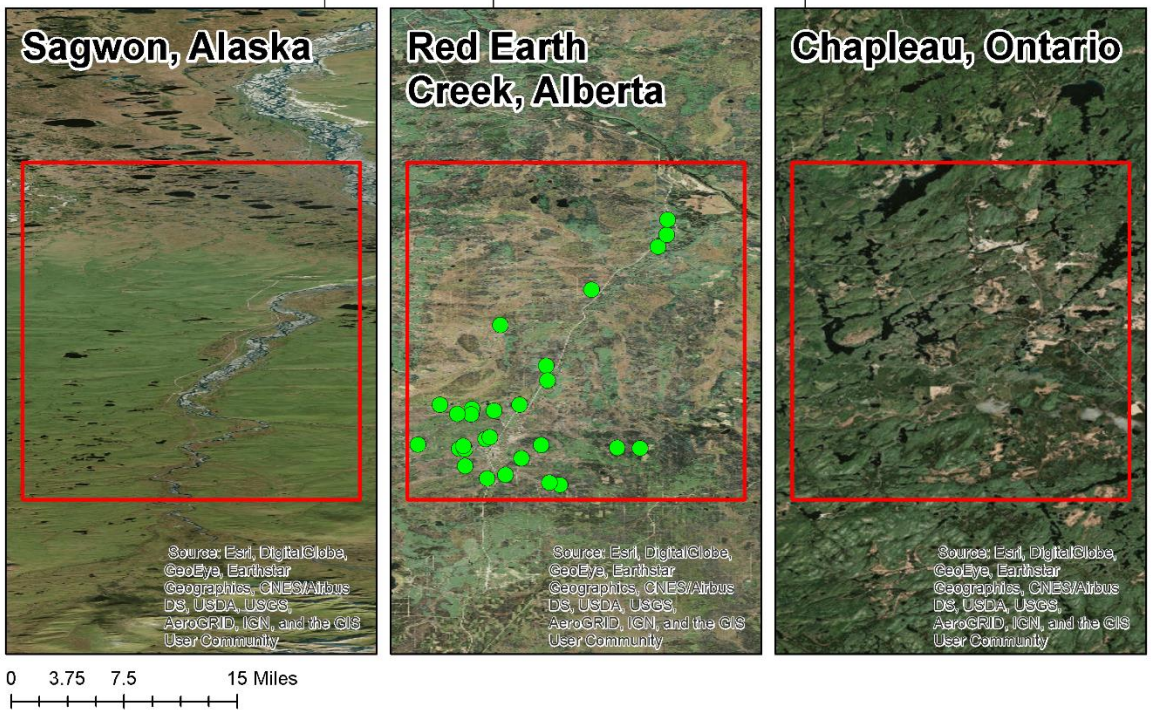
SMAP Field Study 36 km Grid Locations

Tundra - Alaska
Ecosystem Type
tussock tundra
shrubby tundra
mesic/wet sedge tundra
moist shrub tundra (drainages)

Boreal Peatlands- Alberta
Ecosystem Types
Wooded Bog
Open Fen
Treed Fen
Deciduous upland
coniferous upland

Boreal Uplands - Ontario
Upland Ecosystem Types
Aspen
Black Spruce
Jack Pine
1991 Burn



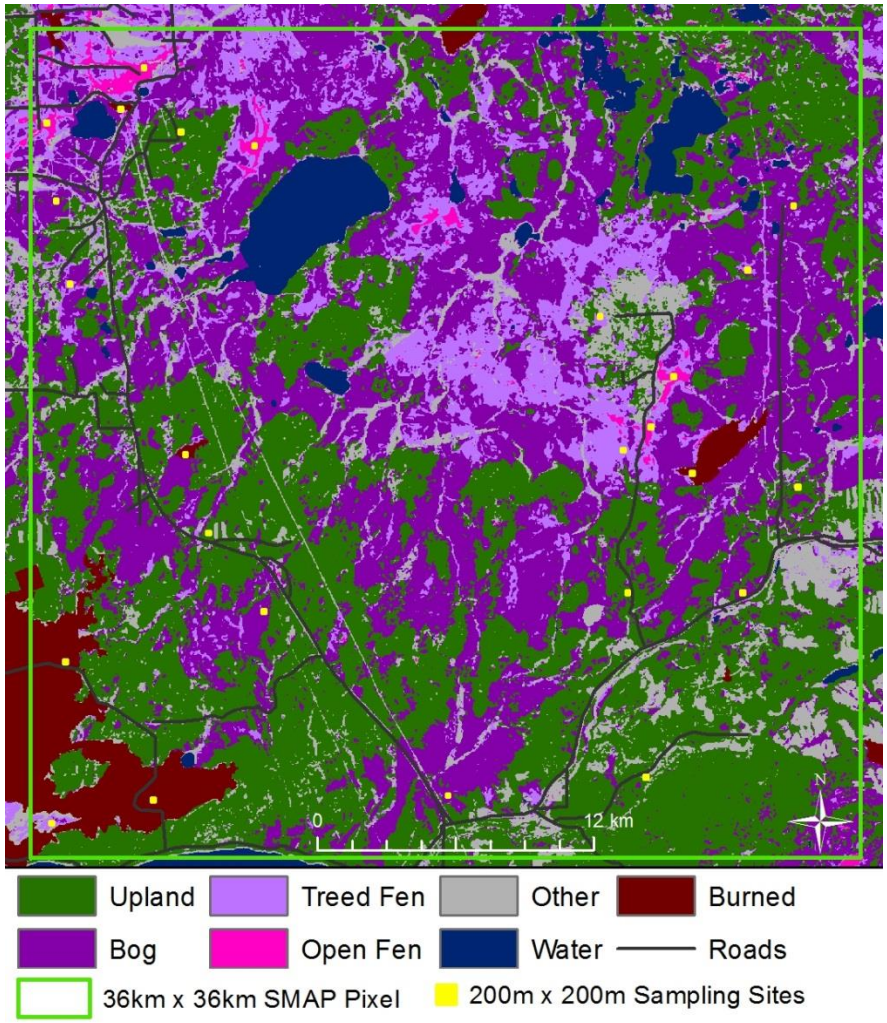


Field Sampling Strategy to Characterize the Spatial Heterogeneity in a SMAP Grid Cell

Within a 36 km SMAP grid will be nested 200 x 200 m sites stratified by cover type within each ecosystem type (boreal peatland, tundra, boreal upland).

Peatland cover type map of Alberta region with a 36 km simulated SMAP pixel demonstrates the spatial heterogeneity.

Each cover type will have 3-5 200 x 200 m sites sampled across the 36 km grid cell.



Obj. 3: Investigate downscaling SMAP to finer resolution with integration of SAR

- Compare passive SMAP data with high-resolution SAR imagery to:
  1. address the impact of scene heterogeneity and surface water on SMAP results; and
  2. investigate methods for downscaling to a finer resolution (0.2 to 3 km) soil moisture product through
     - Re-scaled products will correspond to resolutions between 200 m and 3 km, to facilitate correspondence with MODIS (0.2 to 0.5 km) and weather reanalysis data (3 km).

Summary and Next Steps

- SMAP is showing strong correlations to FWI Drought Code which is representative of 15-20 cm moisture depth; previous work with C-band SAR showed similar strong correlations to DC
  - Add 2016 station-based FWI data for Canada; hopefully that improves network coverage for “recommended quality” retrievals
  - Region analysis: can we get better model fit by creating region-specific models?
  - Under Development- comparison of SMAP pre-fires to areas burned in 2015-2016
- Work is underway to continue to develop polarimetric algorithms for soil moisture retrieval
- SMAP 36 km grids will be sampled to understand the spatial heterogeneity within a grid cell and
- through high resolution SAR, fully characterize the spatial and temporal radiometric diversity that exists by covertype in tundra, boreal peatland and boreal upland ecotypes

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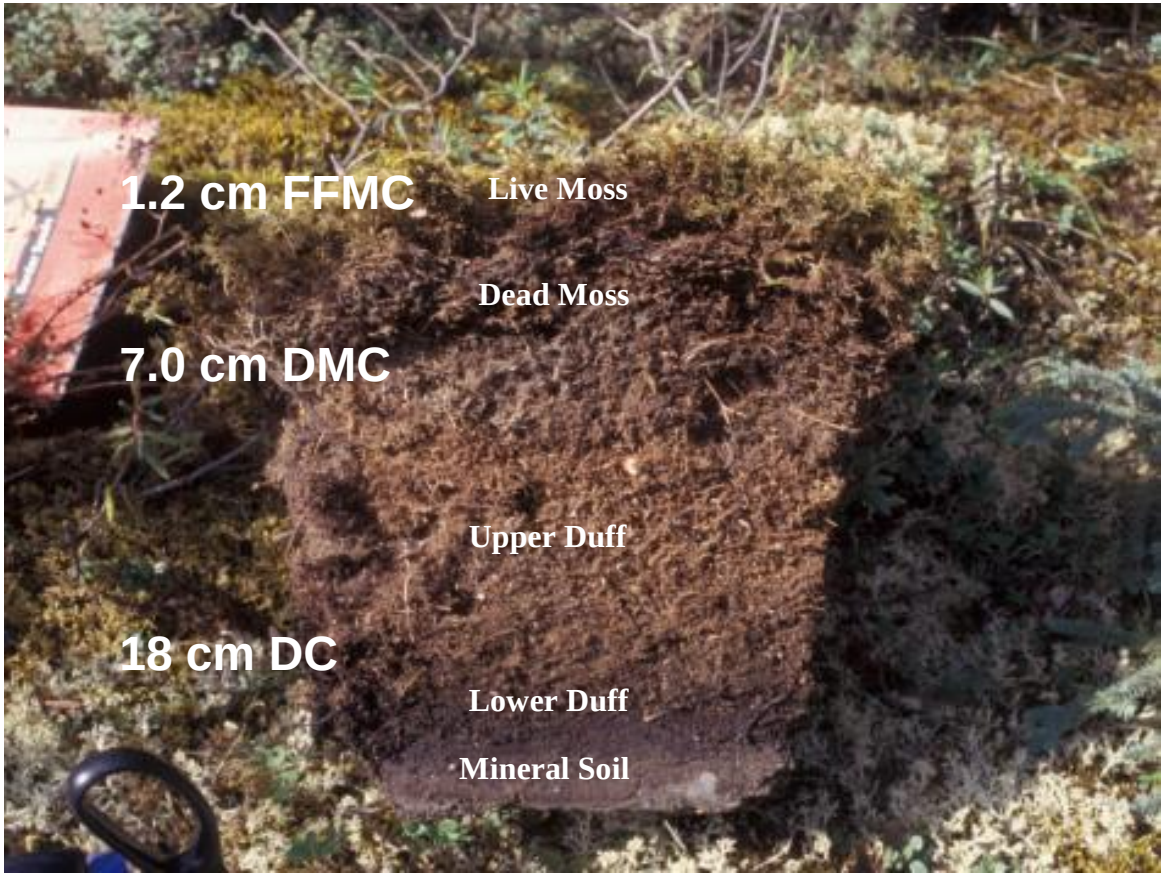
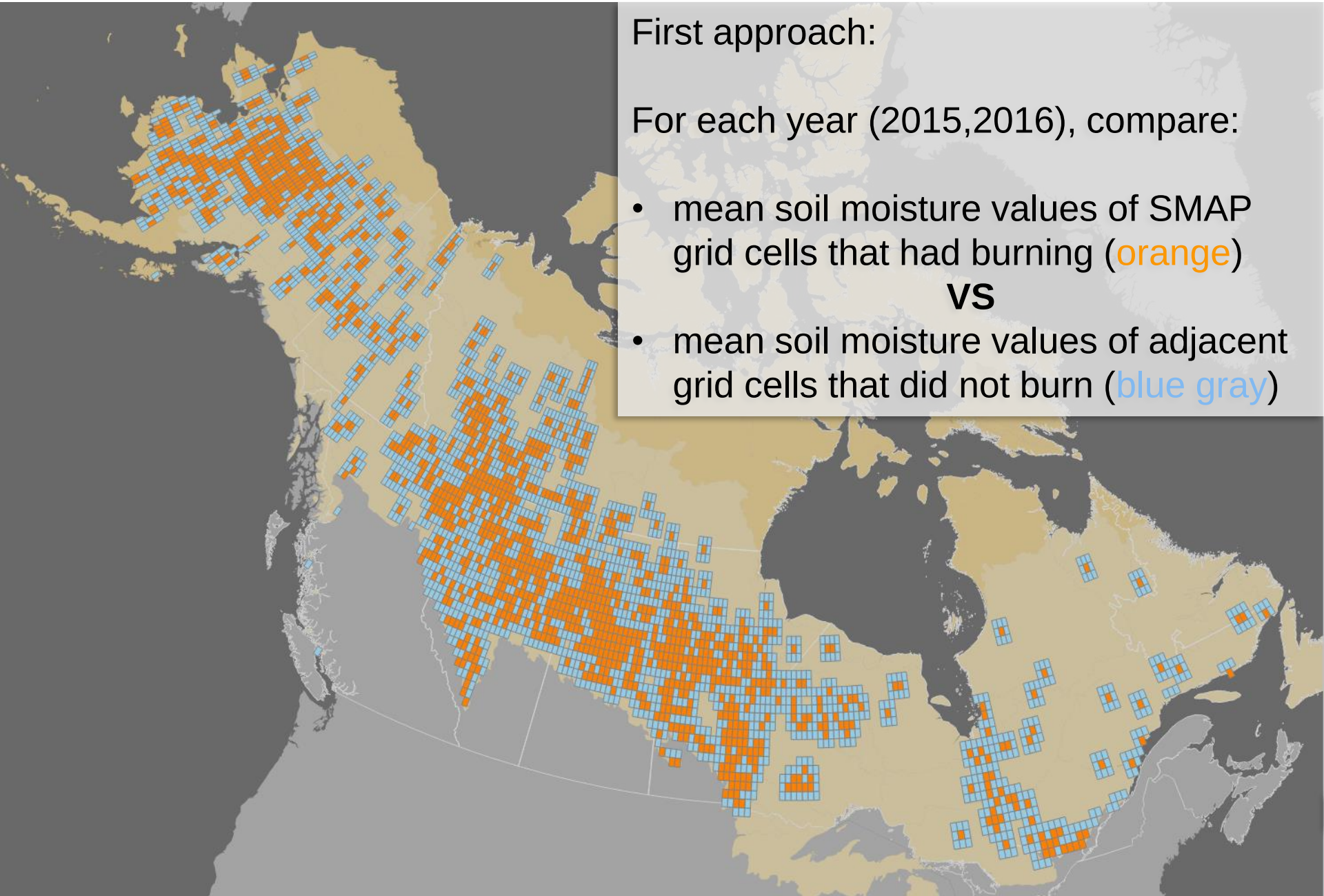


Objective 1:

Evaluate SMAP soil moisture values related to fires

(in progress)

Obj. 1: Evaluate SMAP prior to burns



First approach:

For each year (2015,2016), compare:

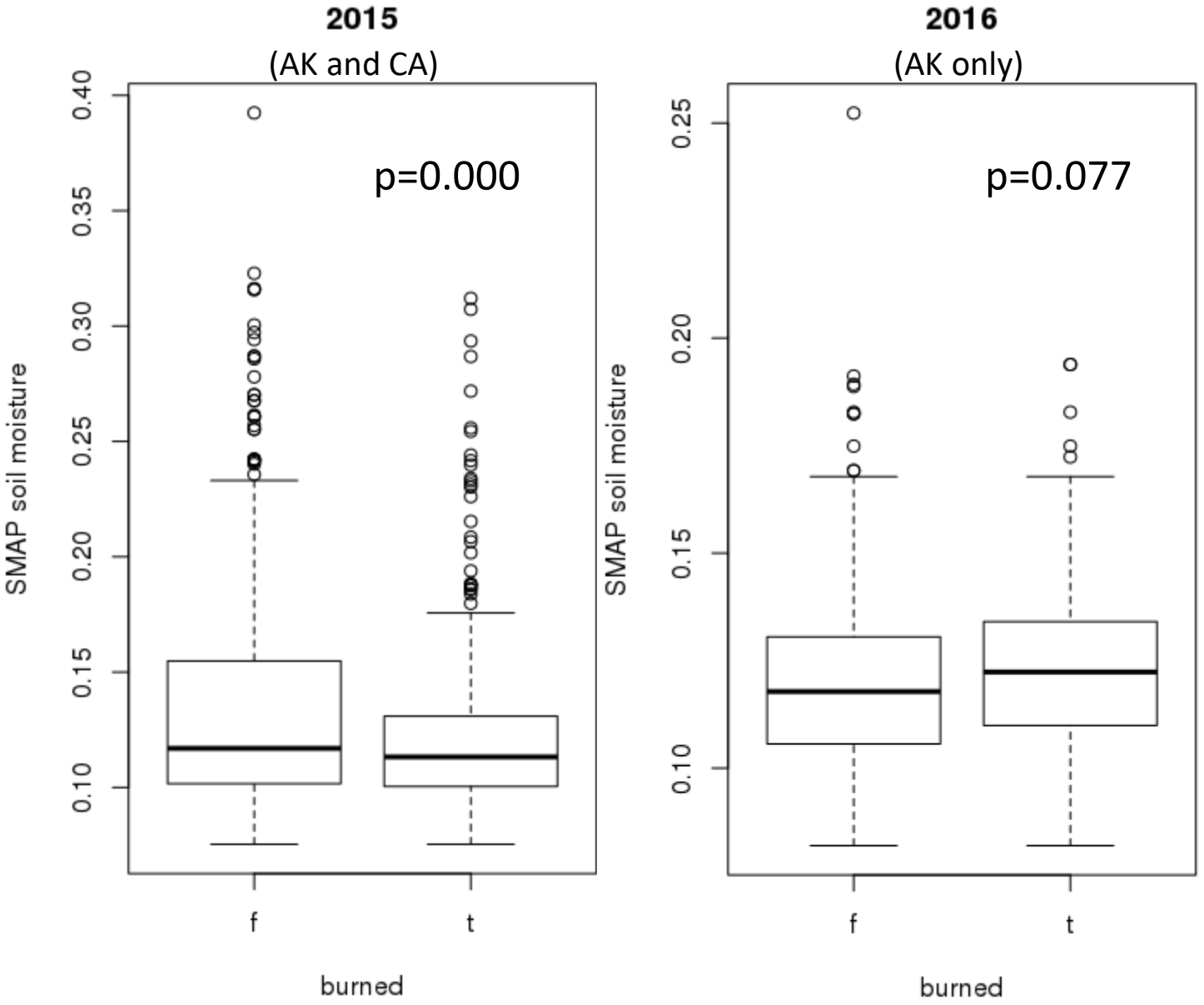
- mean soil moisture values of SMAP grid cells that had burning (orange)

VS

- mean soil moisture values of adjacent grid cells that did not burn (blue gray)

Obj. 1: Evaluate SMAP prior to burns

- Results, first approach:
- Significant difference in burned and non-burned SMAP pixels pre-burn for AK and Canada in 2015
- 2016 AK data only, not-significant



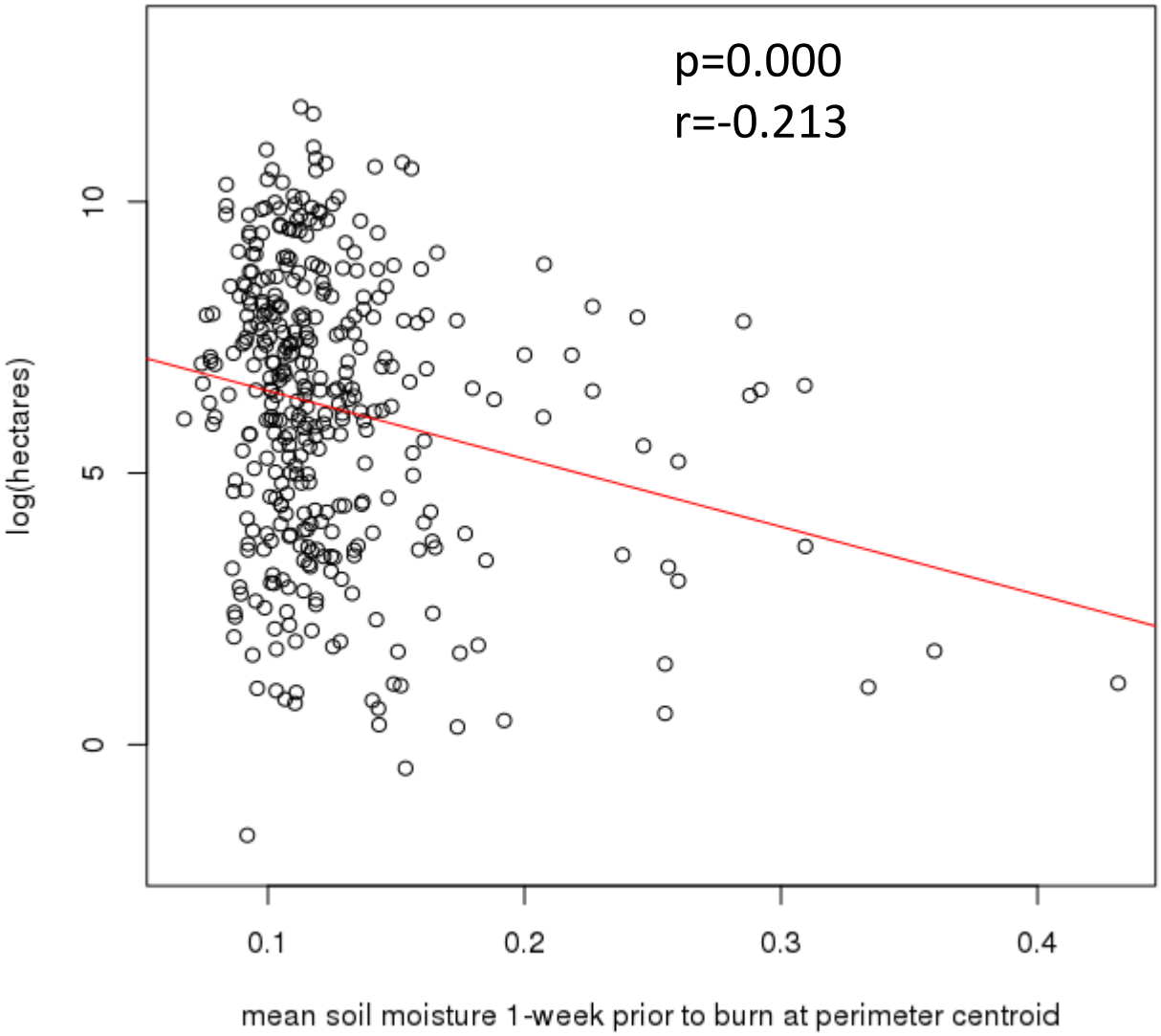
Obj. 1: Evaluate SMAP prior to burns

- Second approach:
  - For each perimeter, compare:
    - mean SMAP-derived soil moisture of burn perimeter 1-week prior to the burn

      vs
    - hectares burned

Obj. 1: Evaluate SMAP prior to burns

- Results, second approach:

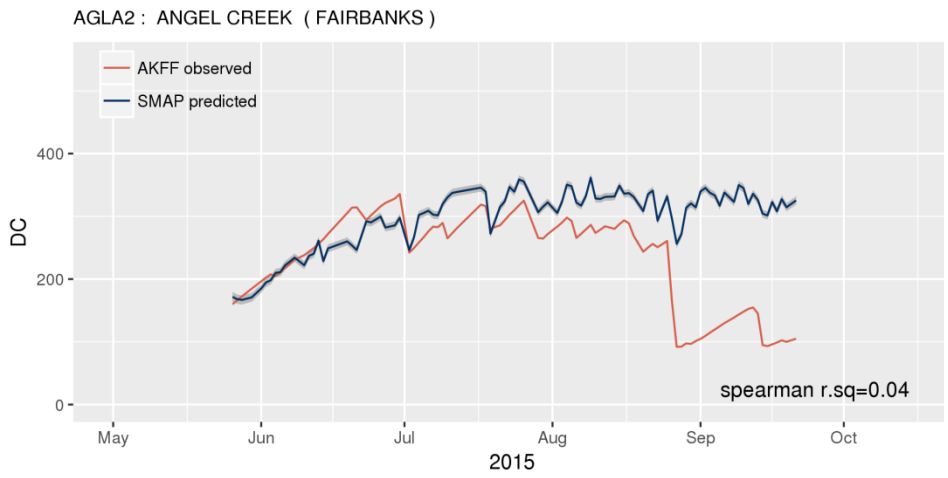


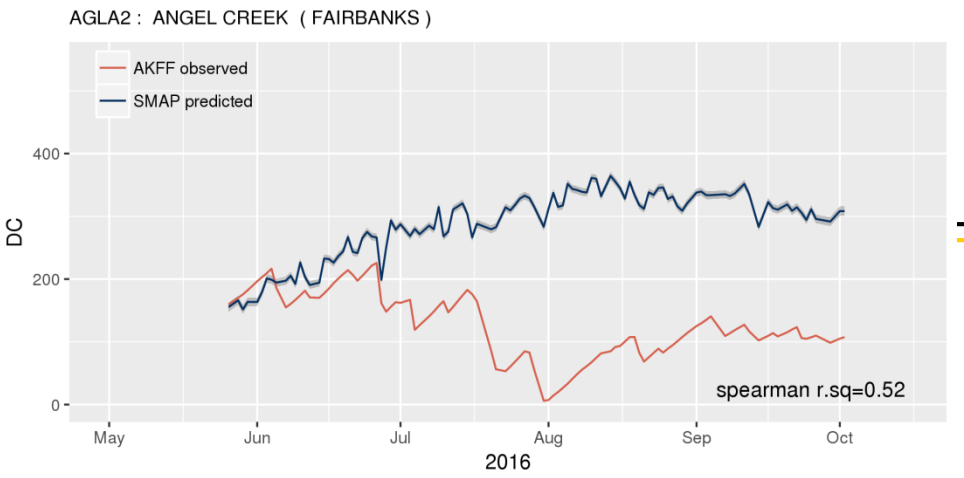
Obj. 2: Evaluate SMAP prior to burns

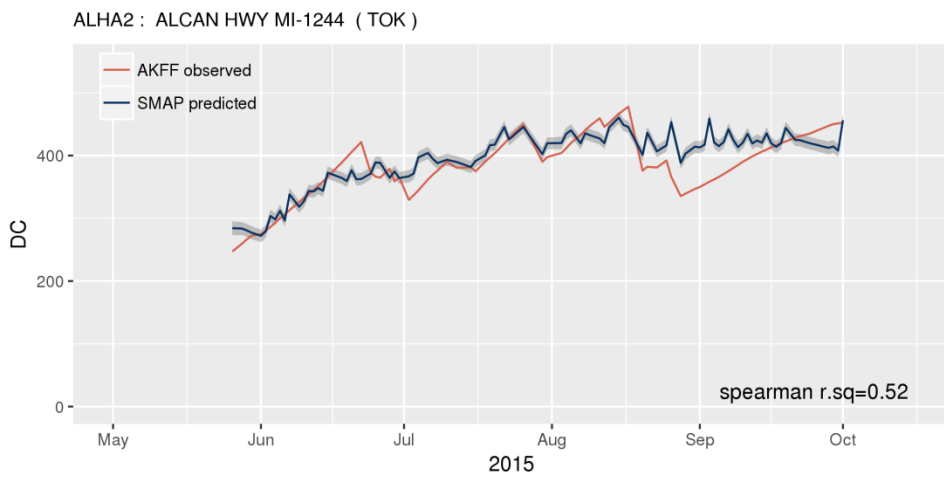
- Next steps:
  - Add 2016 Canada fire perimeter data, re-test 2016
  - Explore additional approaches for determining relationship between pre-burn SMAP-derived soil moisture values w/ burn area
  - Region analysis: are there regions where pre-burn soil moisture is more or less related to burn characteristics?

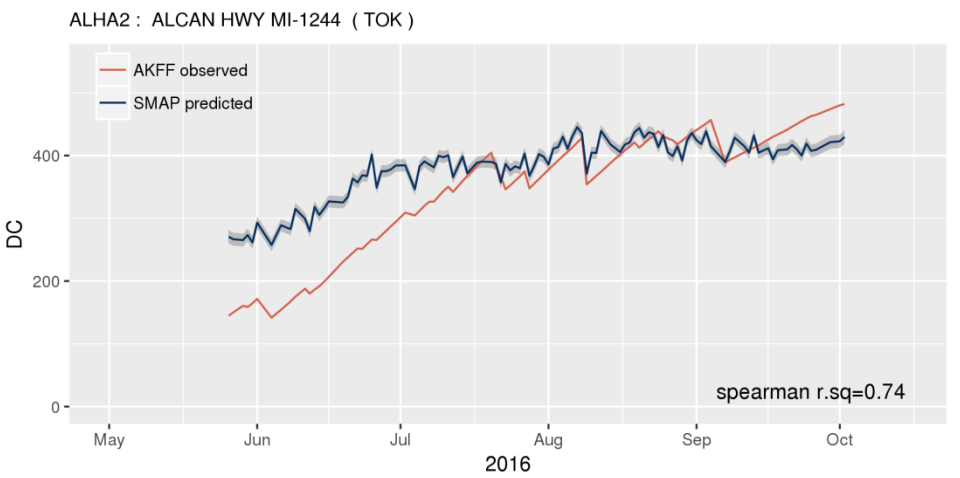
APPENDIX

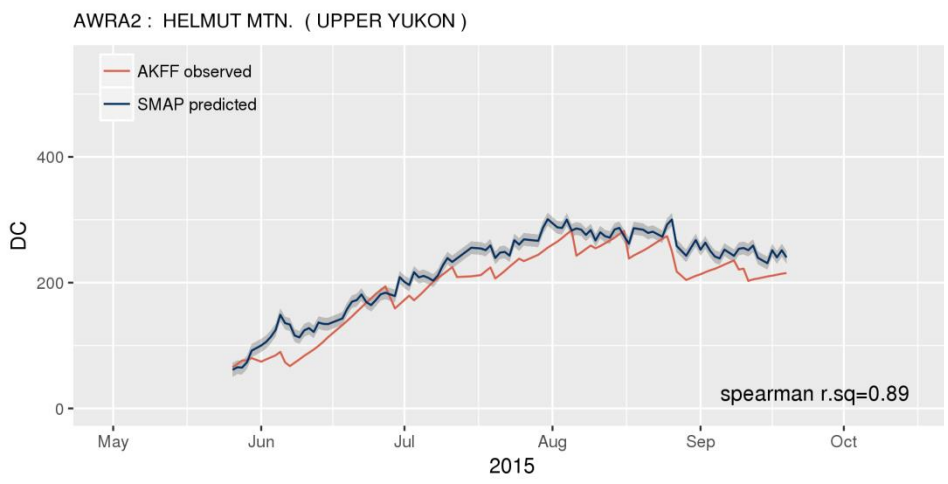
Drought Code (DC) GAM using SMAP data, applied to individual stations (Alaska only)

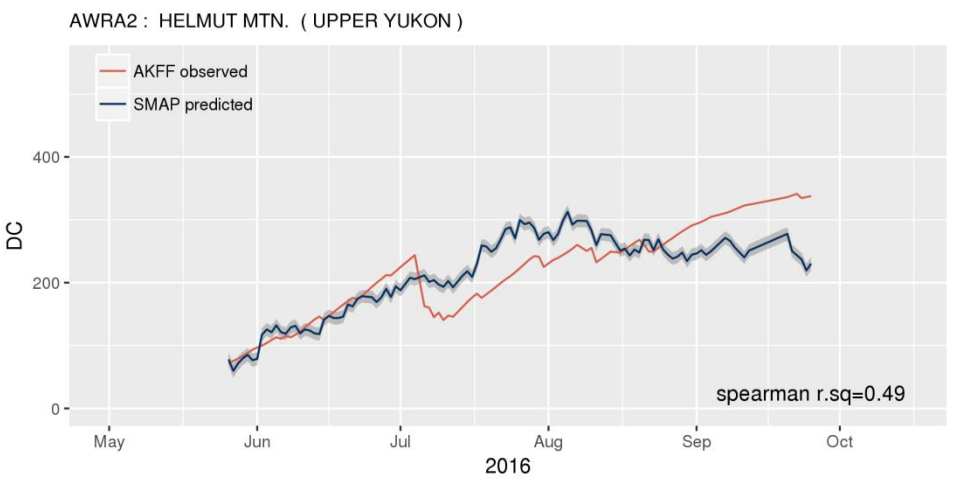

AGLA2 : ANGEL CREEK (FAIRBANKS)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.04


AGLA2 : ANGEL CREEK (FAIRBANKS)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.52

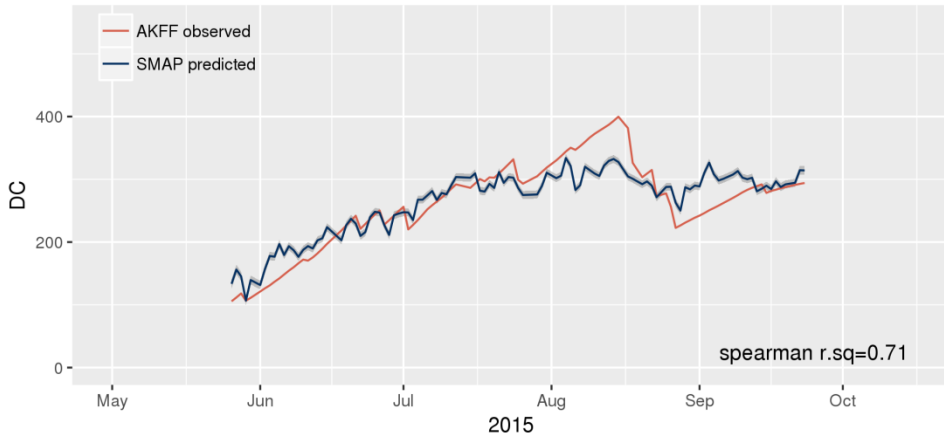

ALHA2 : ALCAN HWY MI-1244 (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.52


ALHA2 : ALCAN HWY MI-1244 (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.74


AWRA2 : HELMUT MTN. (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.89

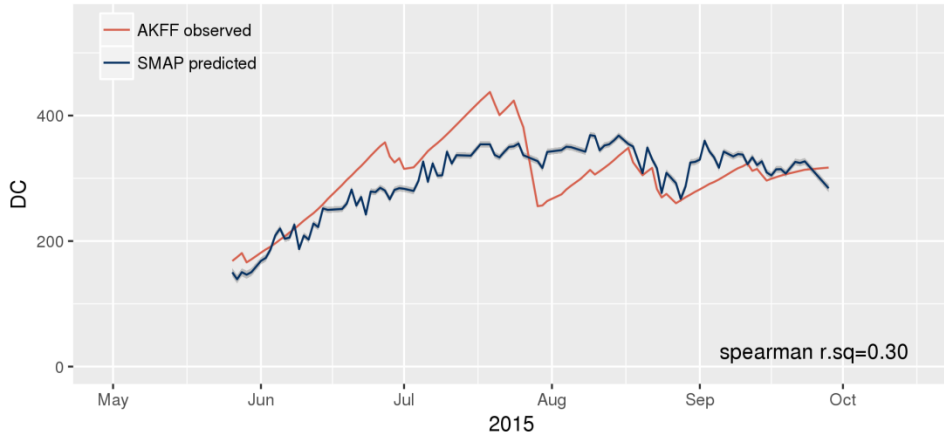

AWRA2 : HELMUT MTN. (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.49

BENA2 : BEN CREEK (UPPER YUKON)

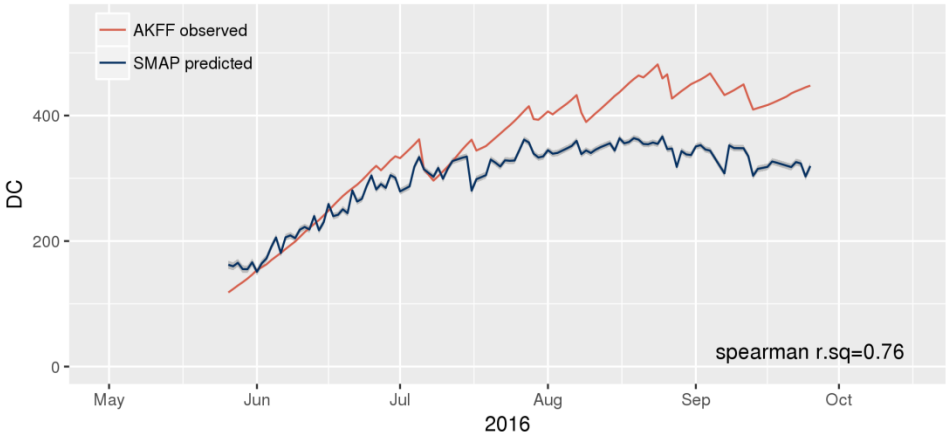


BENA2 : BEN CREEK (UPPER YUKON)

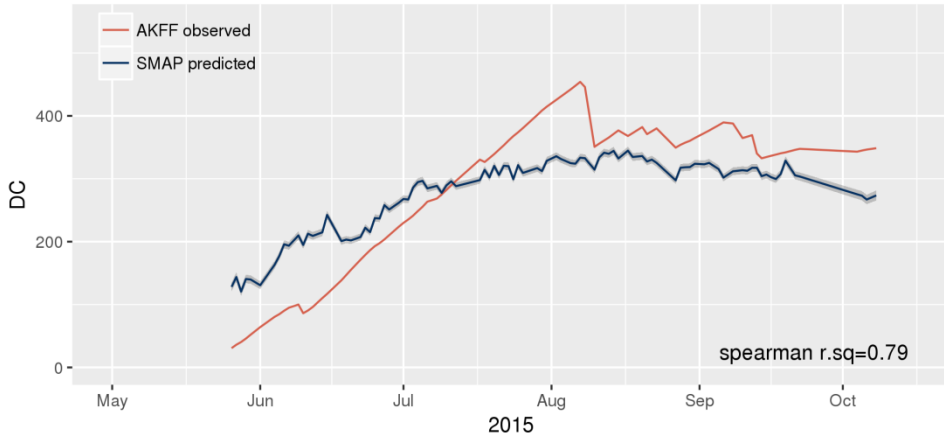
BIRA2 : BIRCH CREEK (UPPER YUKON)



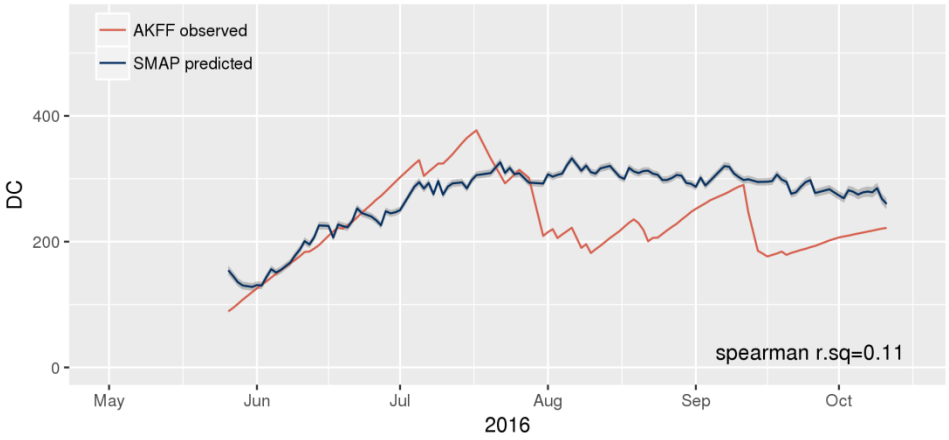
BIRA2 : BIRCH CREEK (UPPER YUKON)

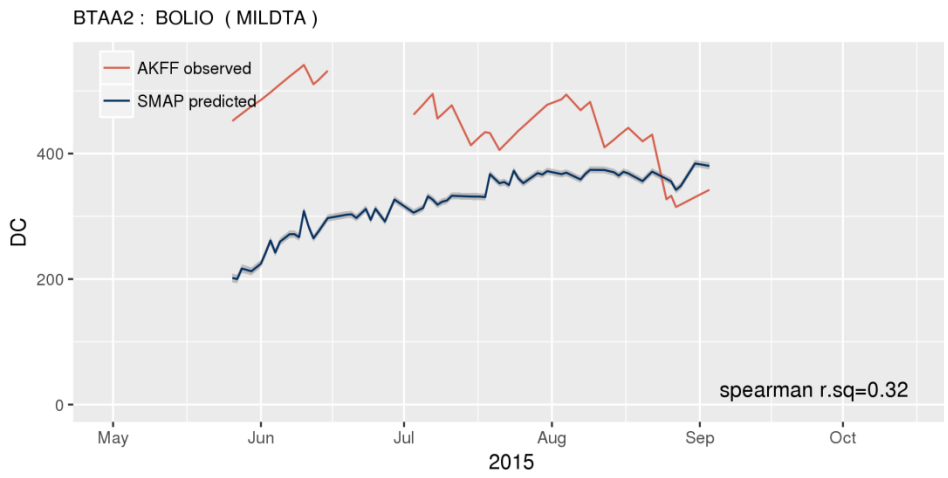


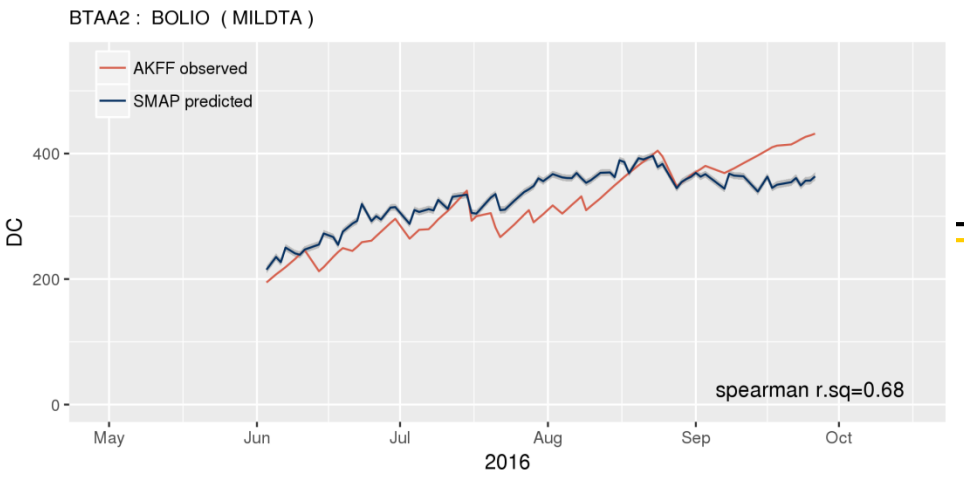
BOXA2 : BOX RIVER (GALENA)

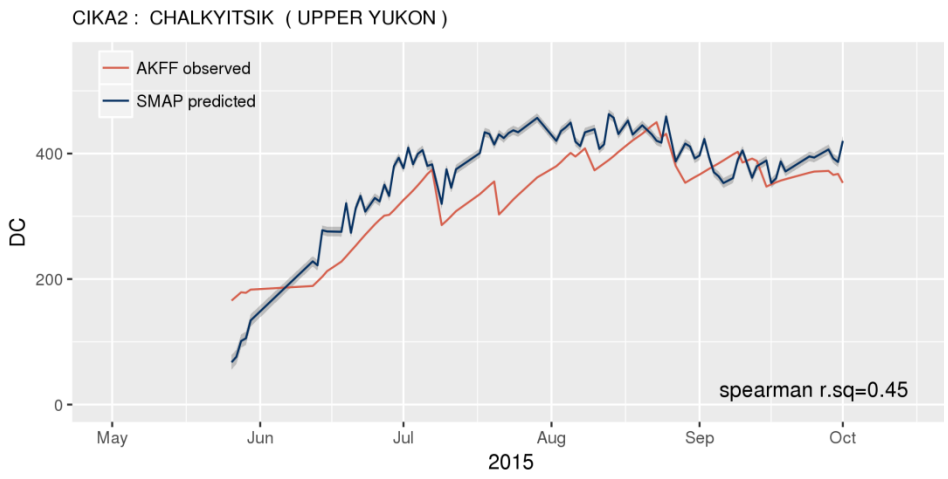


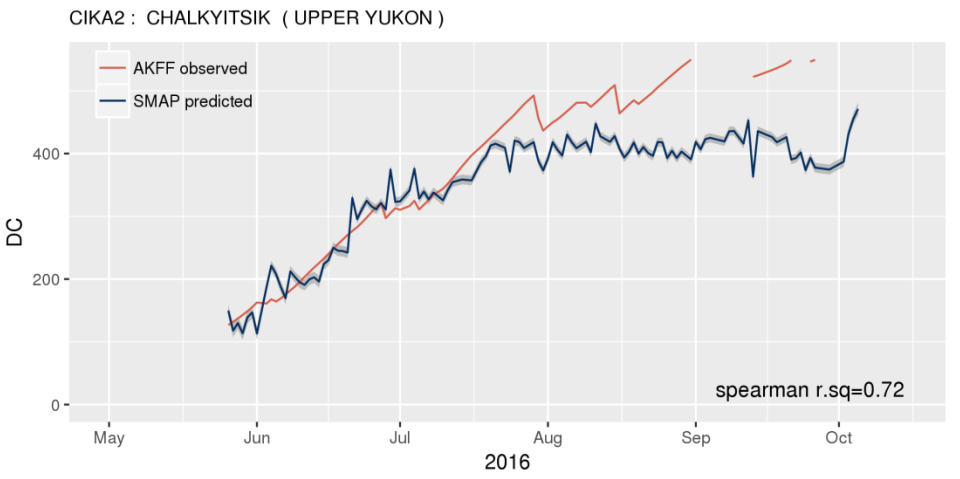
BOXA2 : BOX RIVER (GALENA)

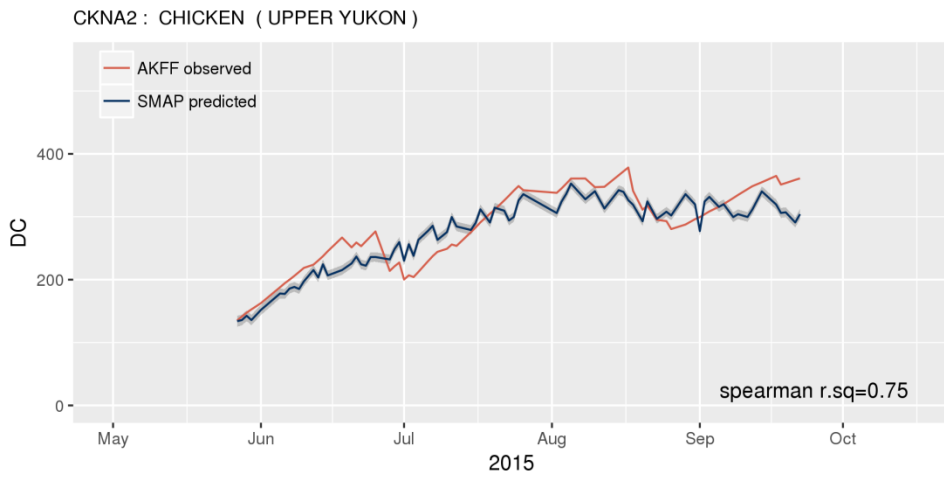


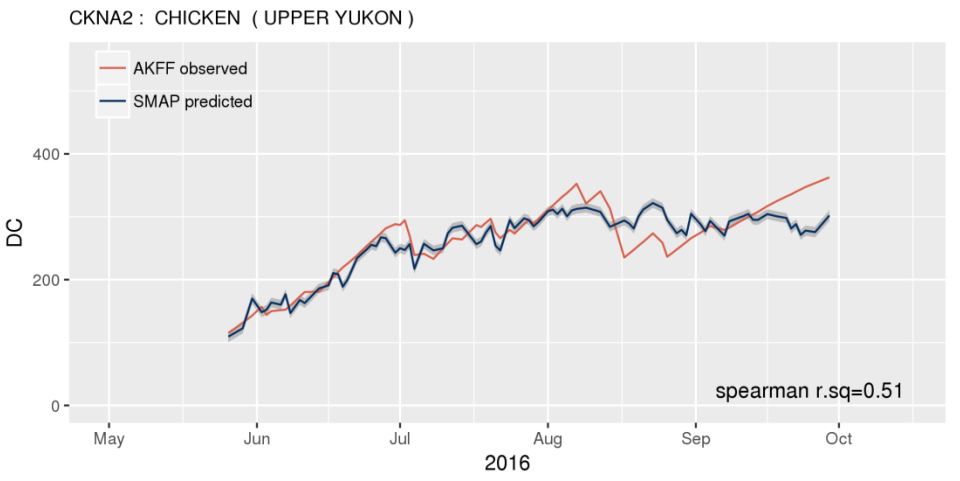

BTAA2 : BOLIO (MILDTA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.32

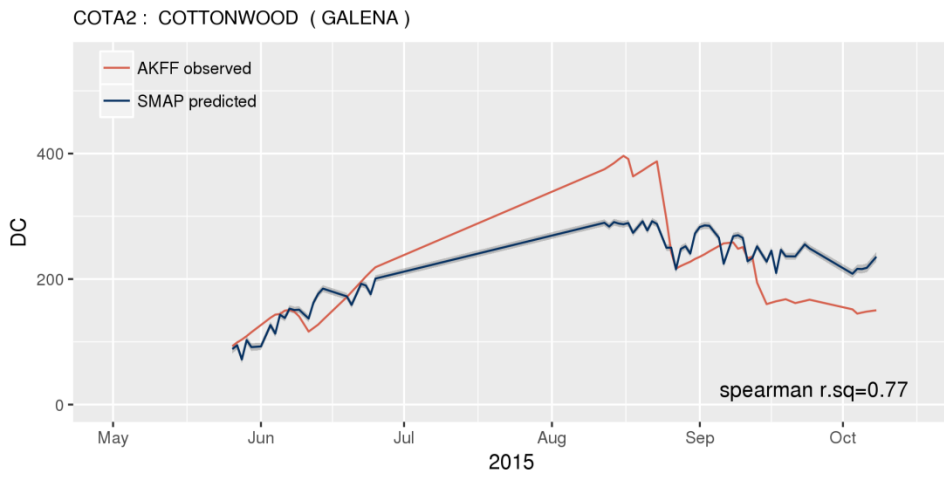

BTAA2 : BOLIO (MILDTA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.68

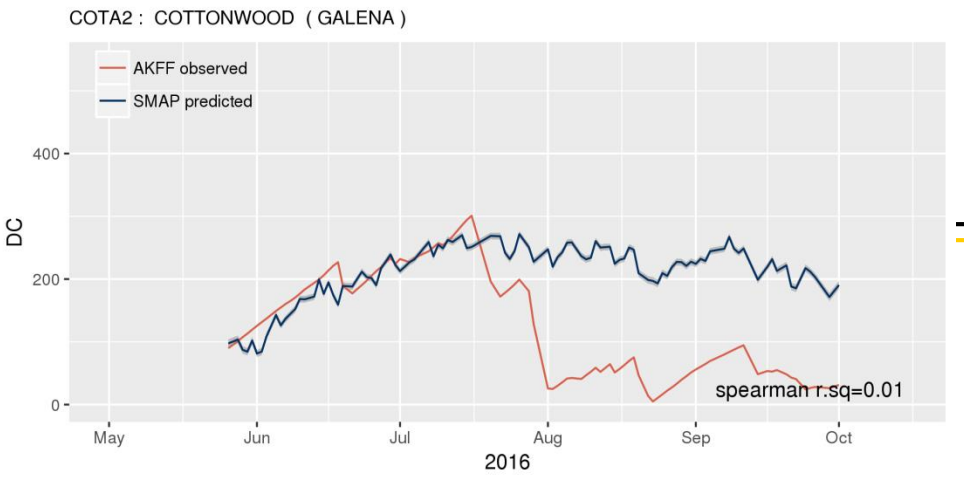

CIKA2 : CHALKYITSIK (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.45

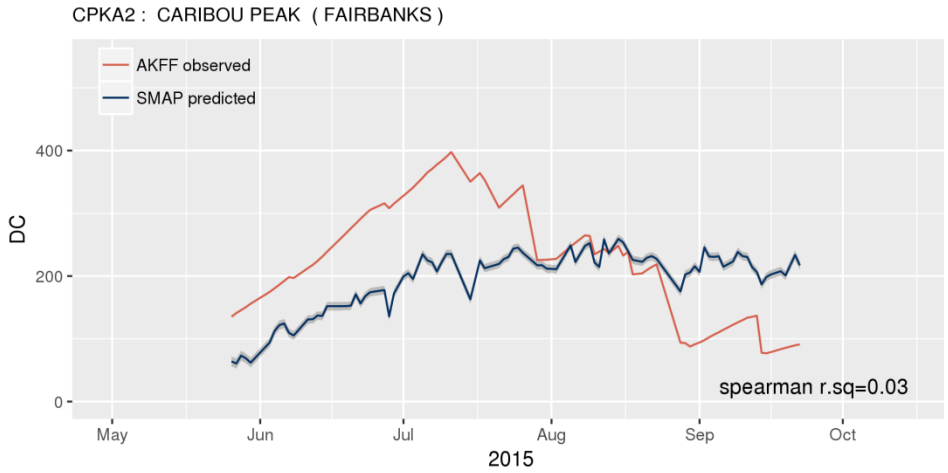

CIKA2 : CHALKYITSIK (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.72

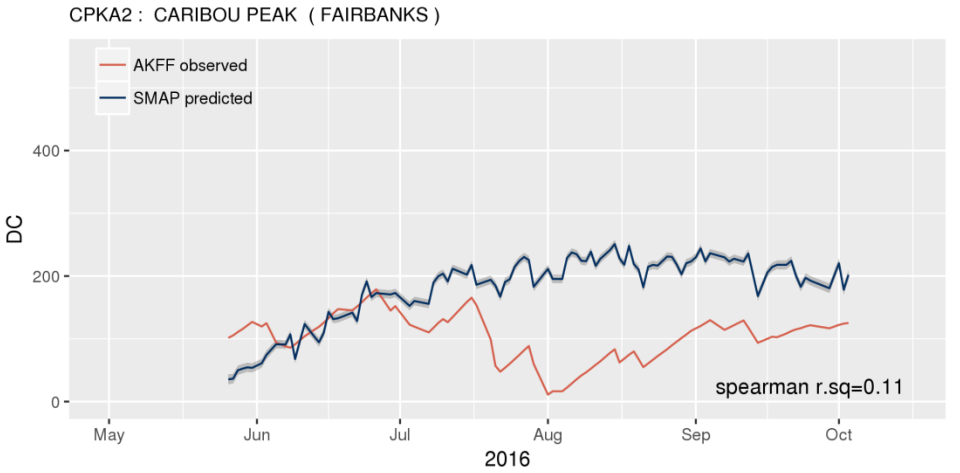

CKNA2 : CHICKEN (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.75

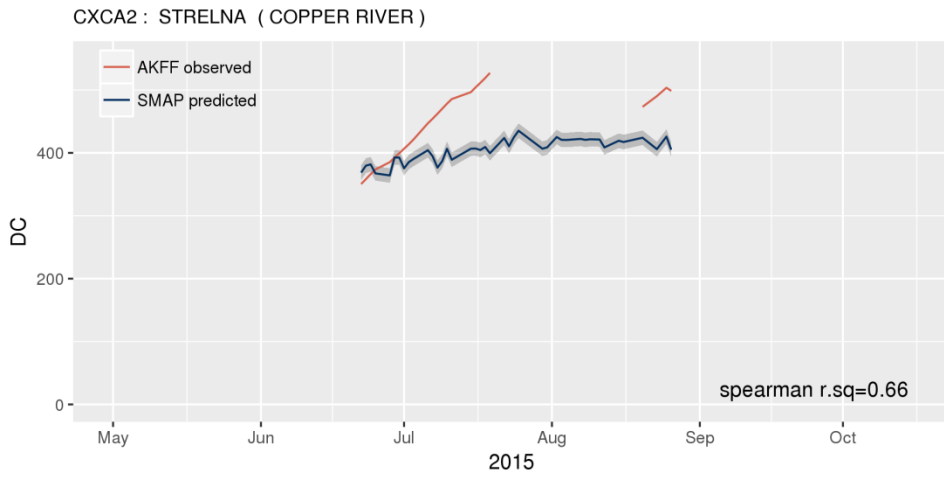

CKNA2 : CHICKEN (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.51

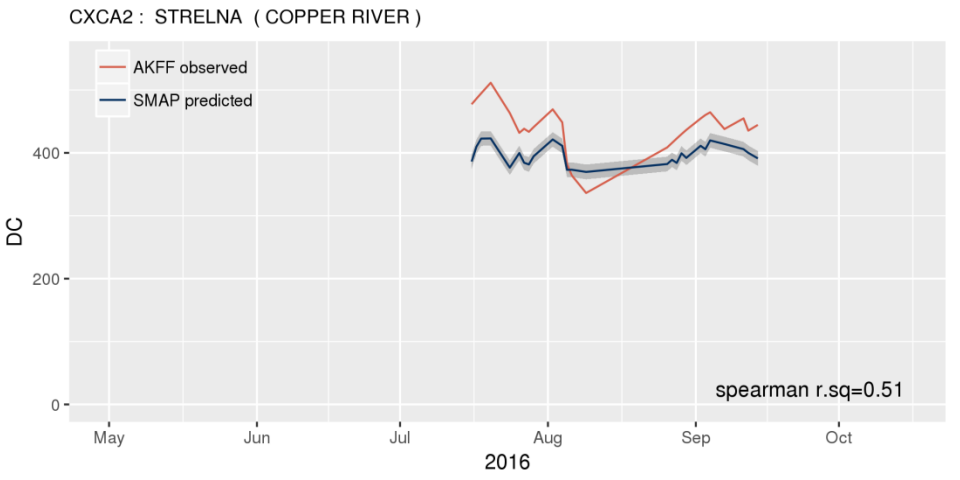

COTA2 : COTTONWOOD (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.77

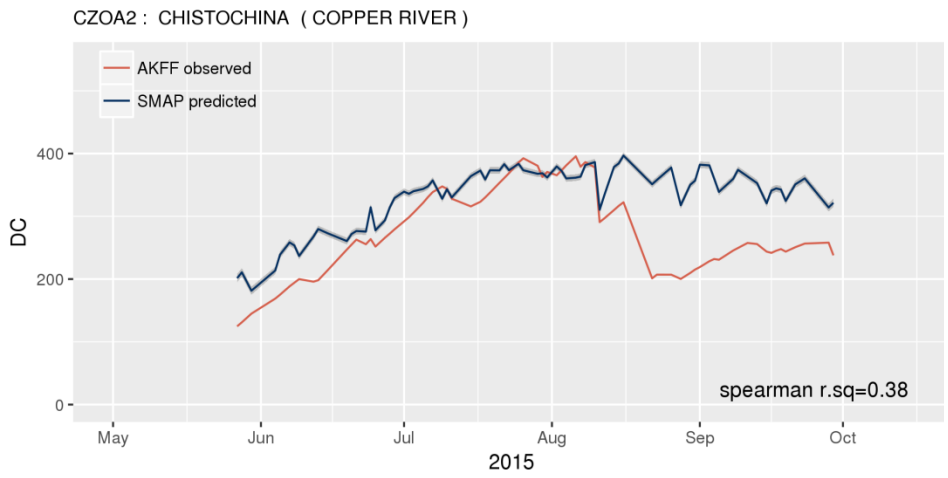

COTA2 : COTTONWOOD (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.01


CPKA2 : CARIBOU PEAK (FAIRBANKS)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.03

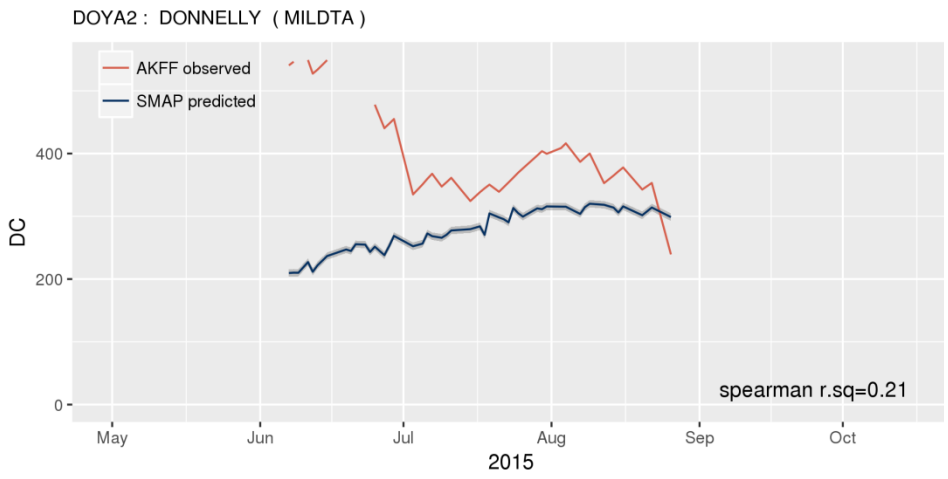

CPKA2 : CARIBOU PEAK (FAIRBANKS)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.11

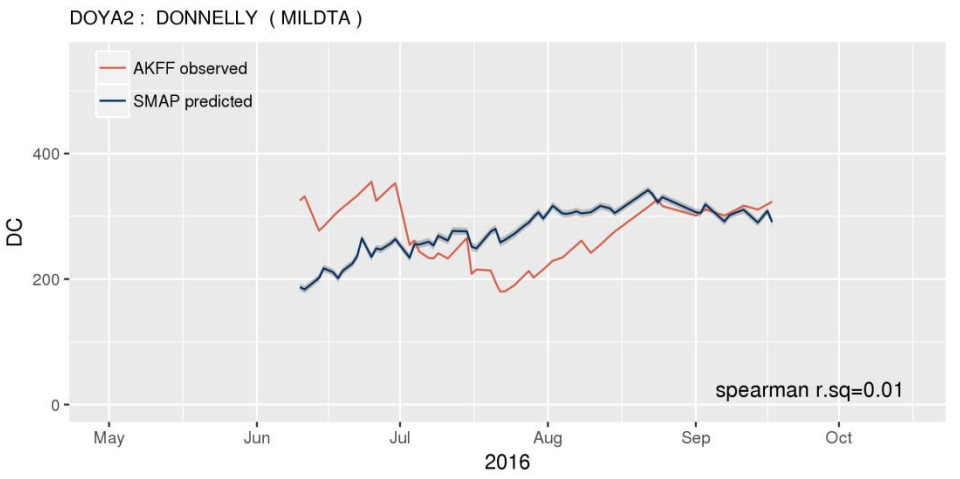

CXCA2 : STRELNA (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.66

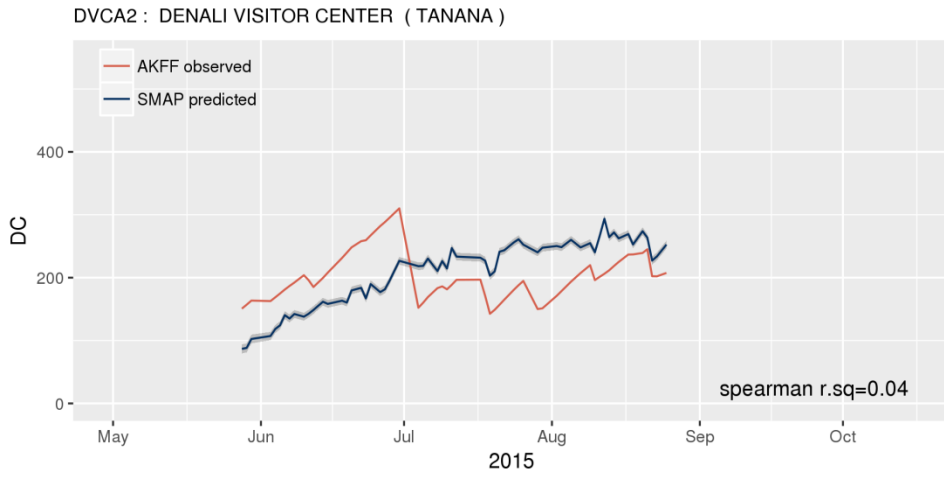

CXCA2 : STRELNA (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.51

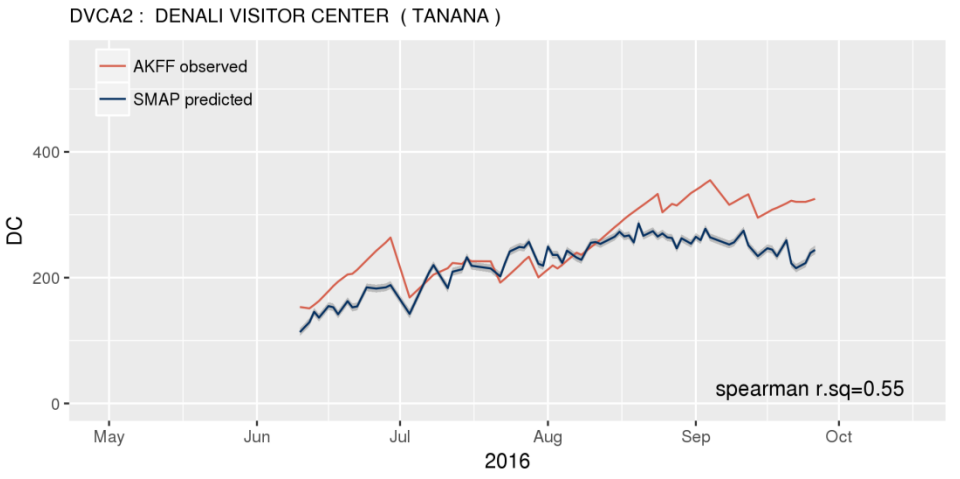

CZOA2 : CHISTOCHINA (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.38


CZOA2 : CHISTOCHINA (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.93

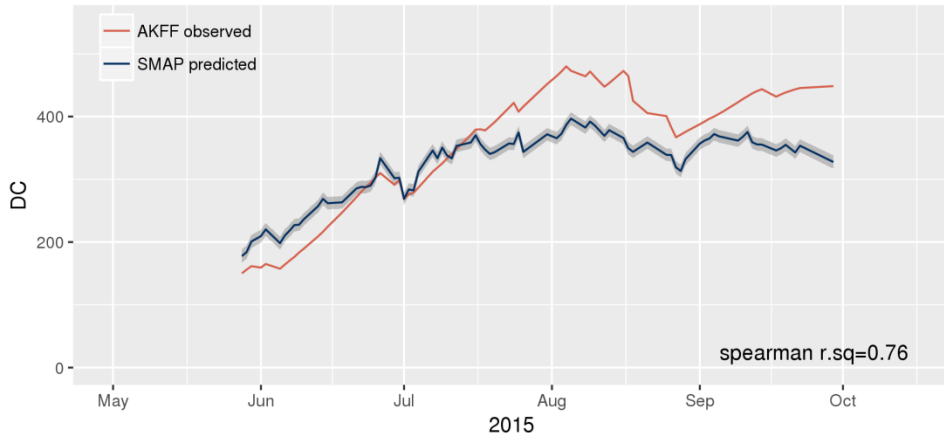

DOYA2 : DONNELLY (MILDTA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.21


DOYA2 : DONNELLY (MILDTA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.01

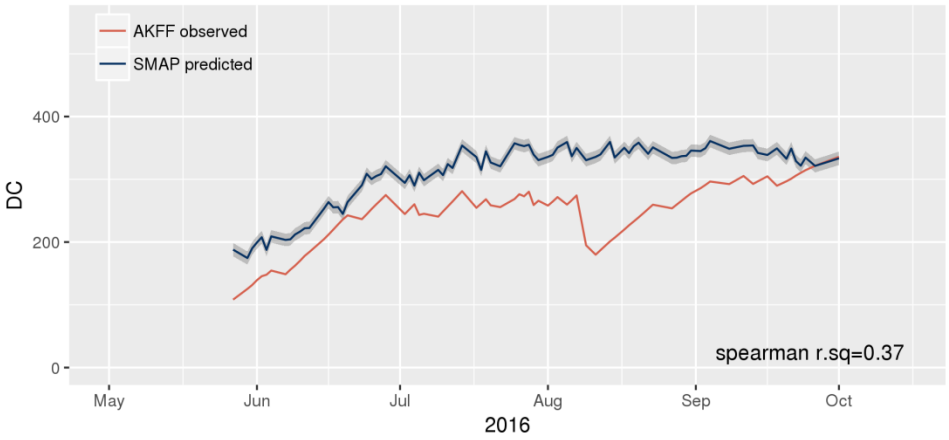

DVCA2 : DENALI VISITOR CENTER (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.04


DVCA2 : DENALI VISITOR CENTER (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.55

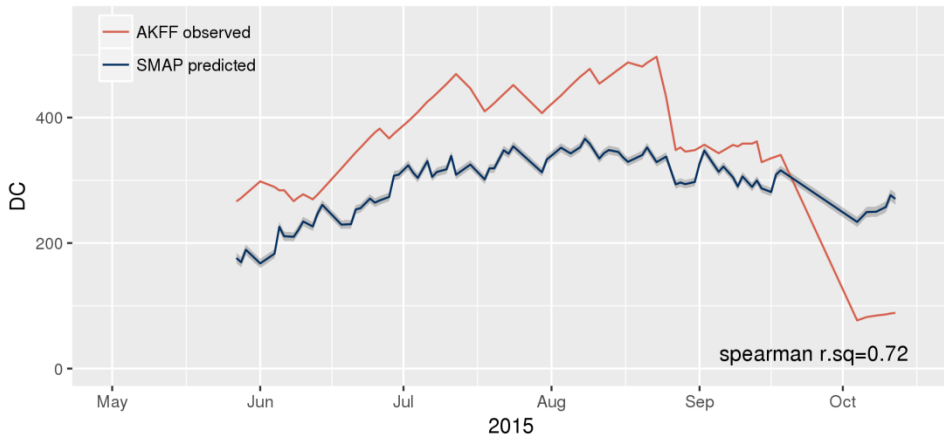
EGYA2 : EAGLE (UPPER YUKON)



EGYA2 : EAGLE (UPPER YUKON)

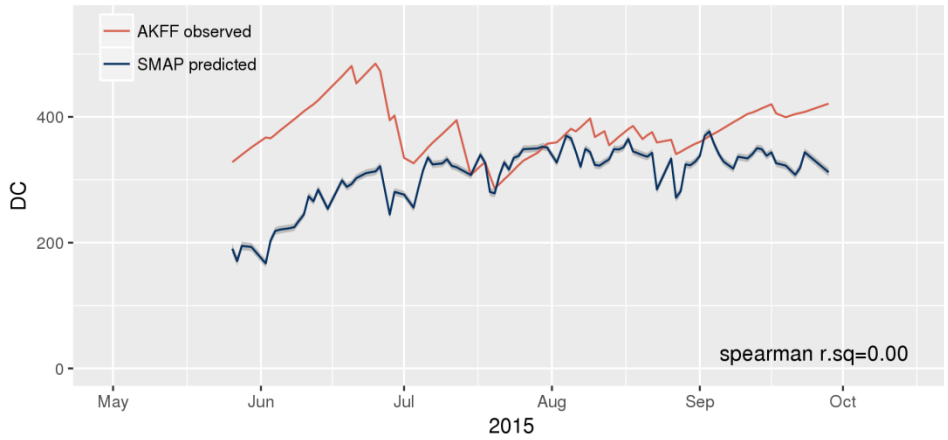


FWLA2 : FAREWELL (SOUTHWEST)

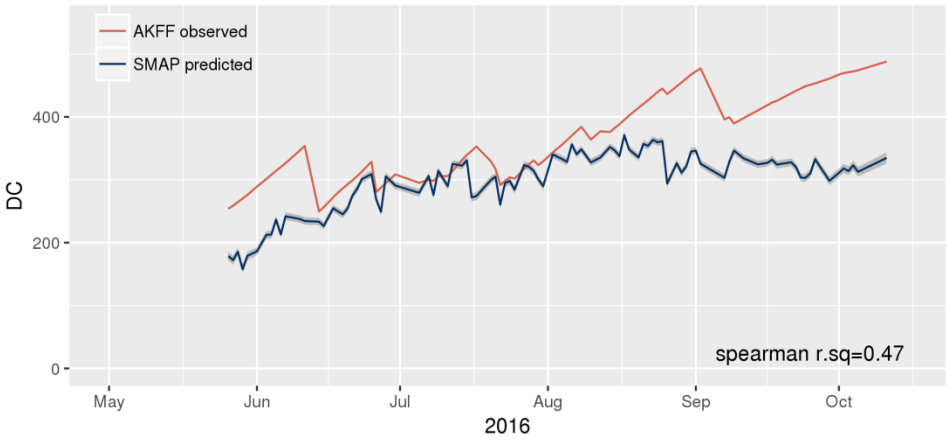


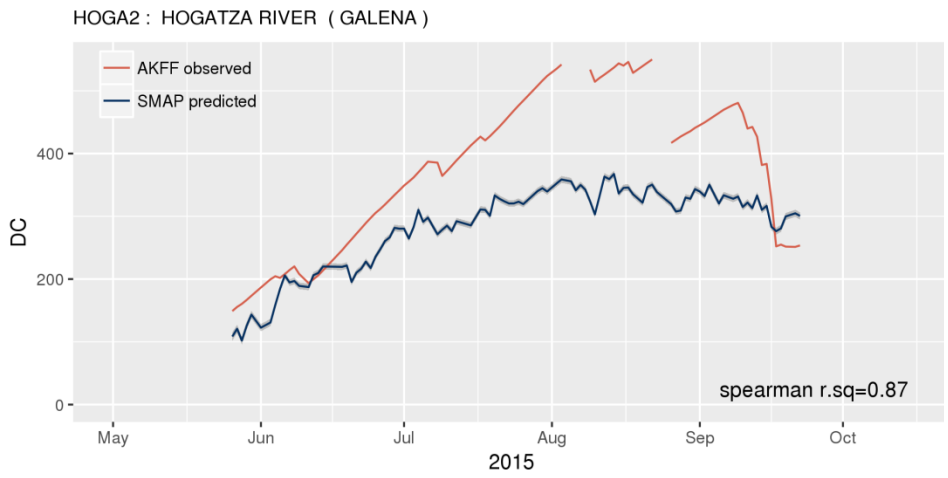
FWLA2 : FAREWELL (SOUTHWEST)

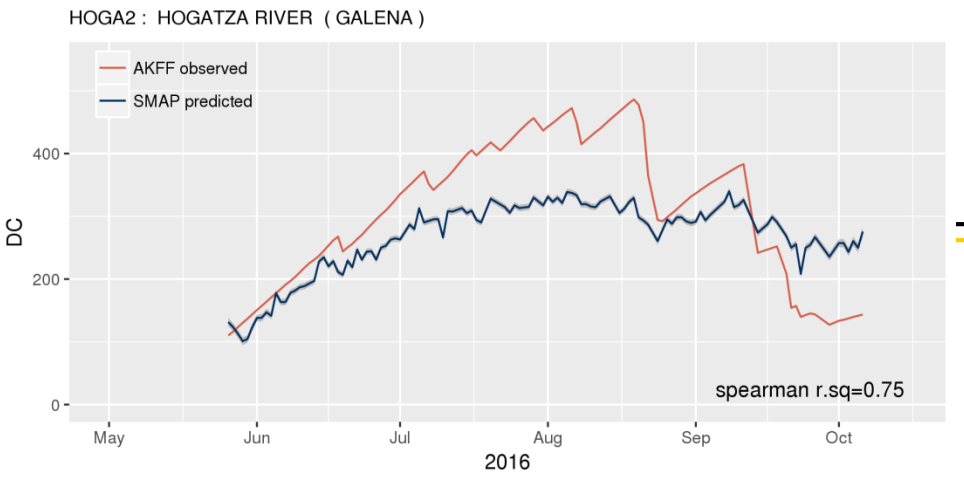
GDPA2 : GOODPASTURE (DELTA)

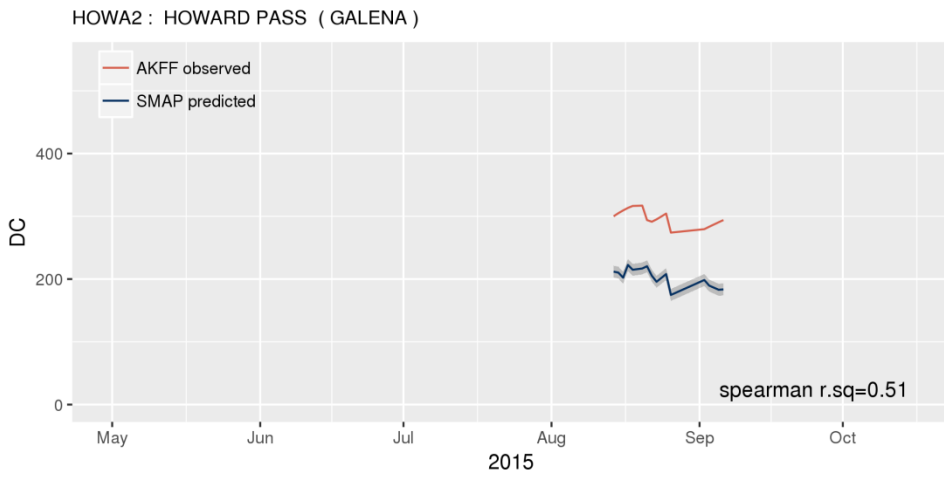


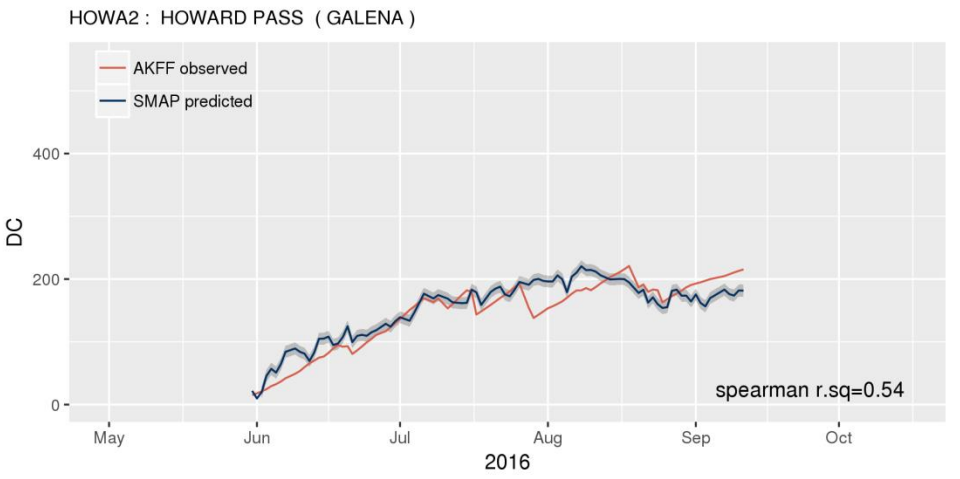
GDPA2 : GOODPASTURE (DELTA)

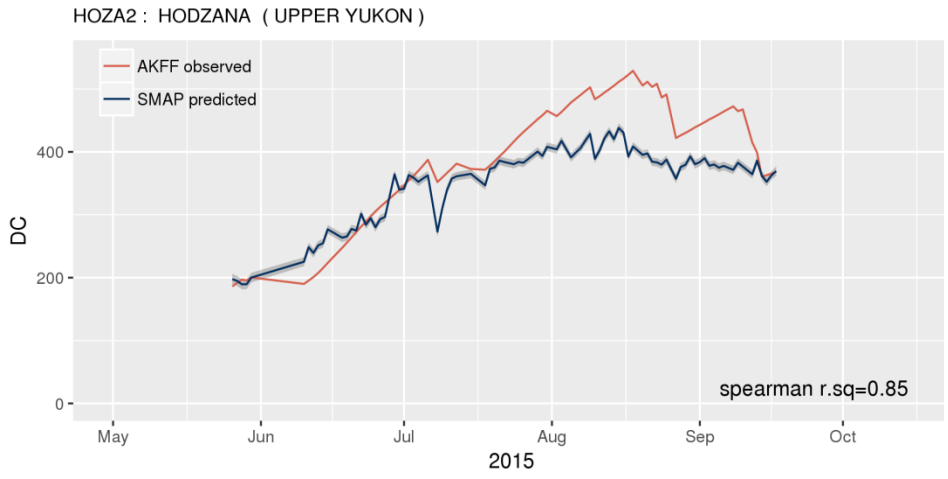


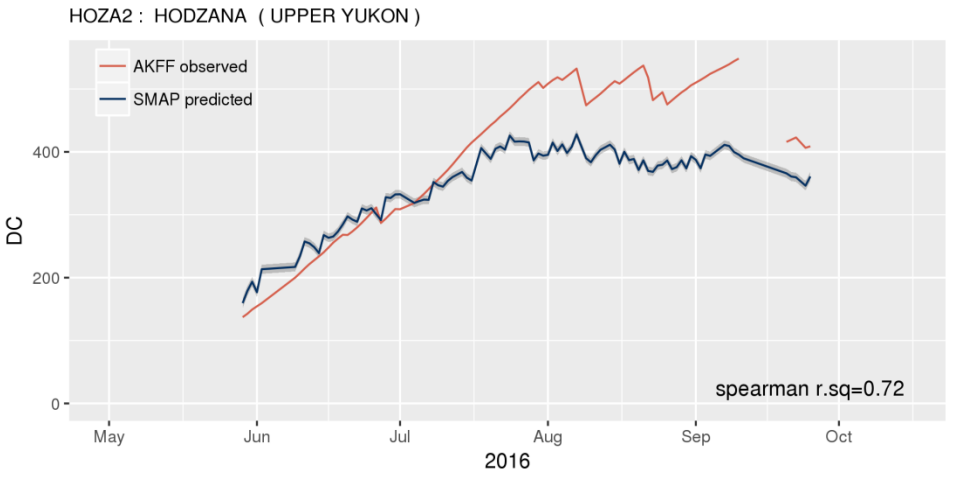

HOGA2 : HOGATZA RIVER (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.87


HOGA2 : HOGATZA RIVER (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.75

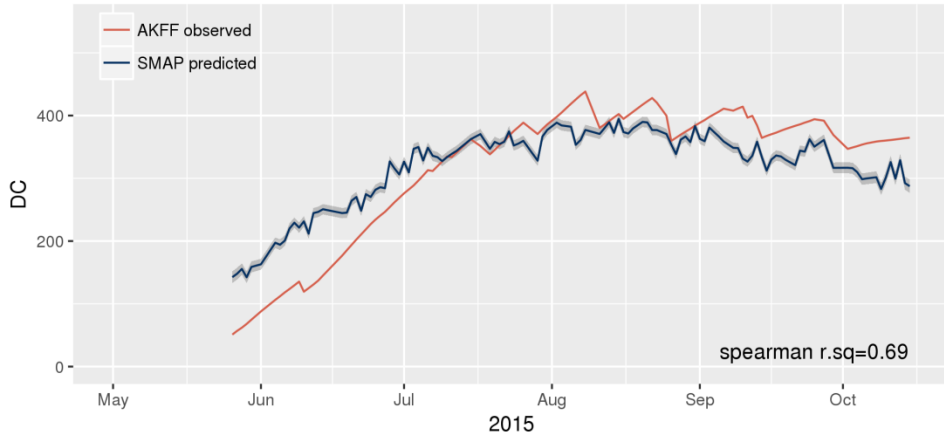

HOWA2 : HOWARD PASS (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.51


HOWA2 : HOWARD PASS (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.54

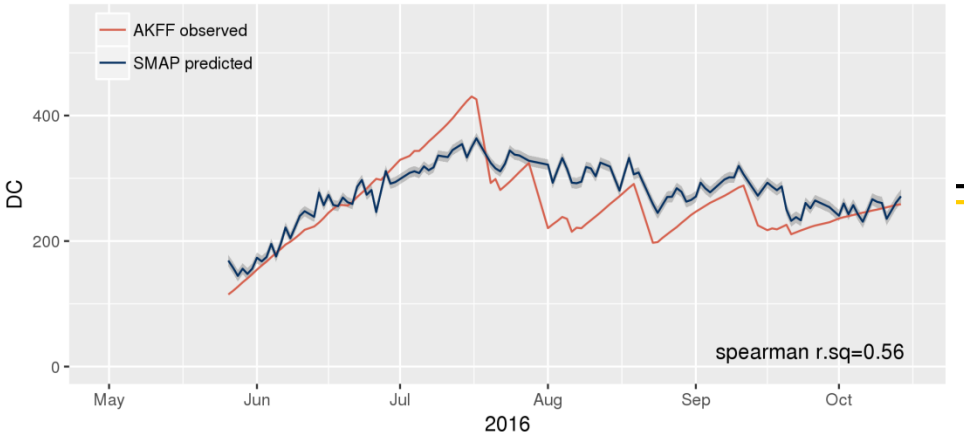

HOZA2 : HODZANA (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.85


HOZA2 : HODZANA (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.72

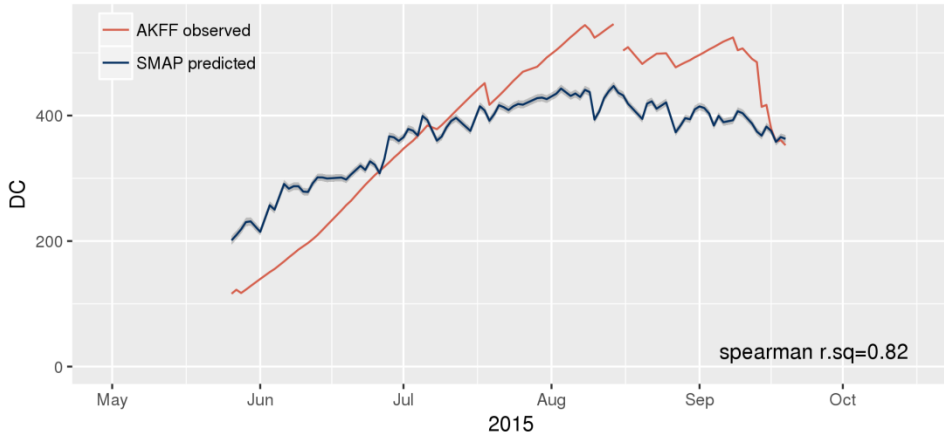
KAIA2 : KAIYUH (GALENA)



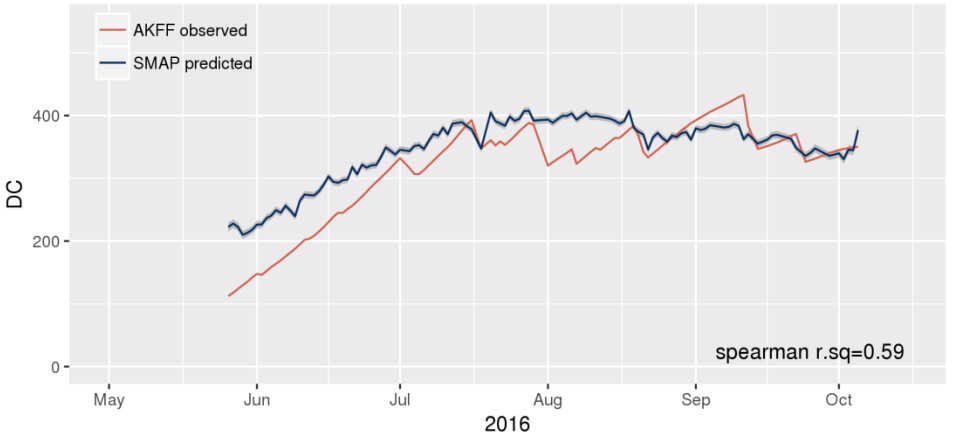
KAIA2 : KAIYUH (GALENA)



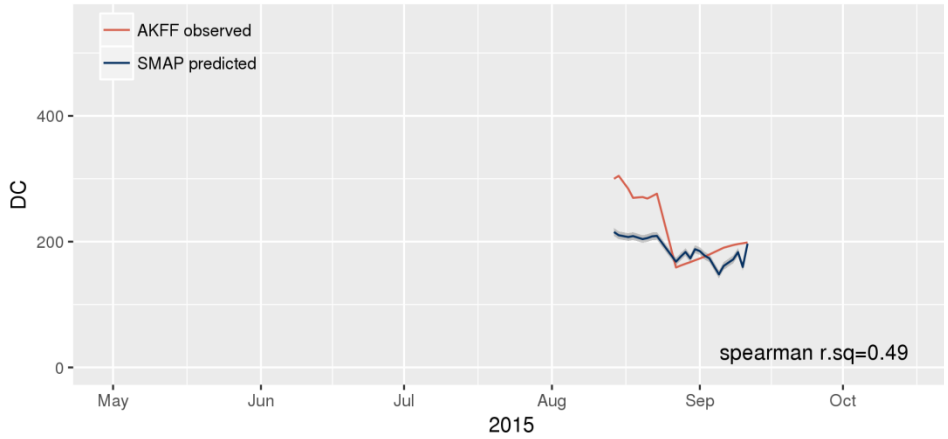
KANA2 : KANUTI NWR (TANANA)



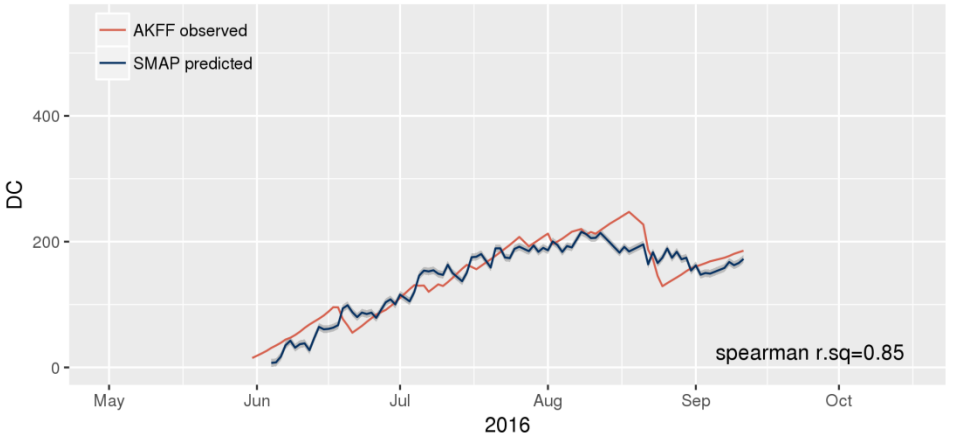
KANA2 : KANUTI NWR (TANANA)

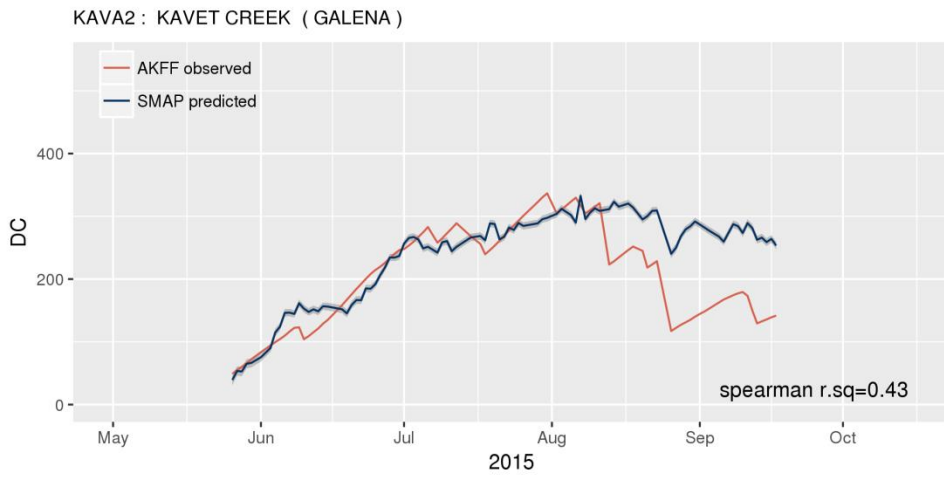


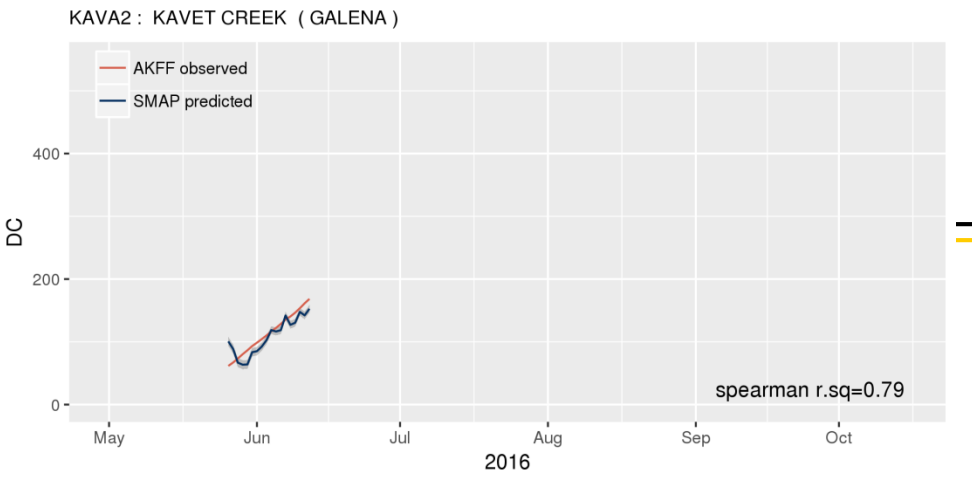
KAUA2 : KALUICH (GALENA)

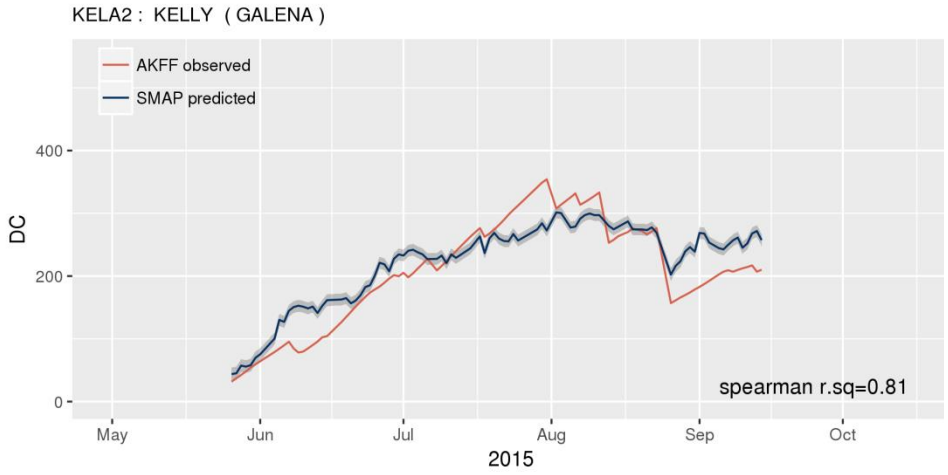


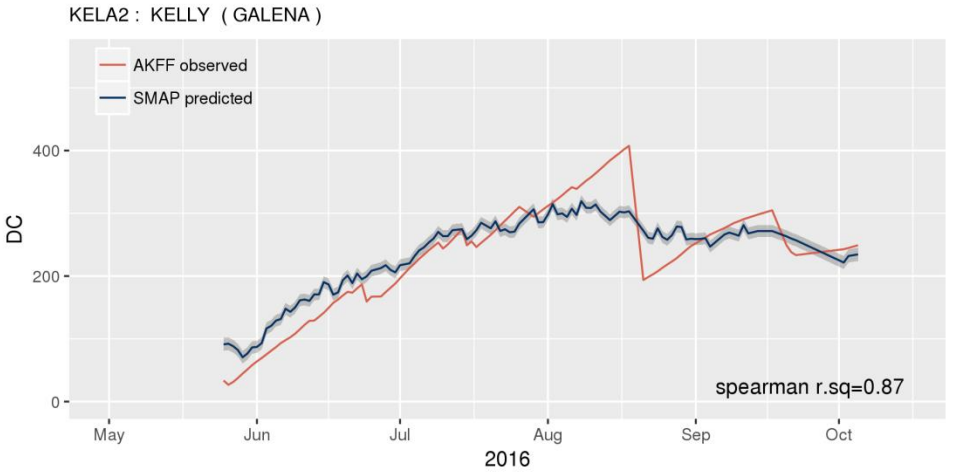
KAUA2 : KALUICH (GALENA)

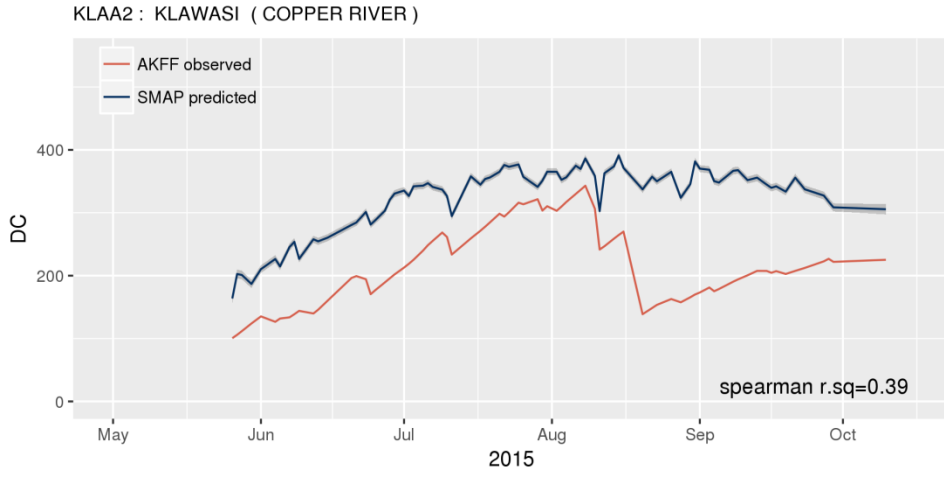


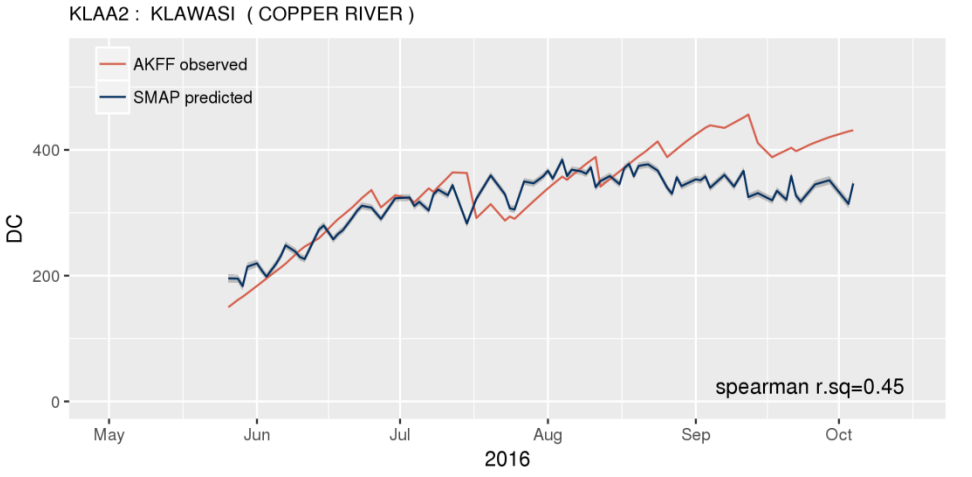

KAVA2 : KAVET CREEK (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.43

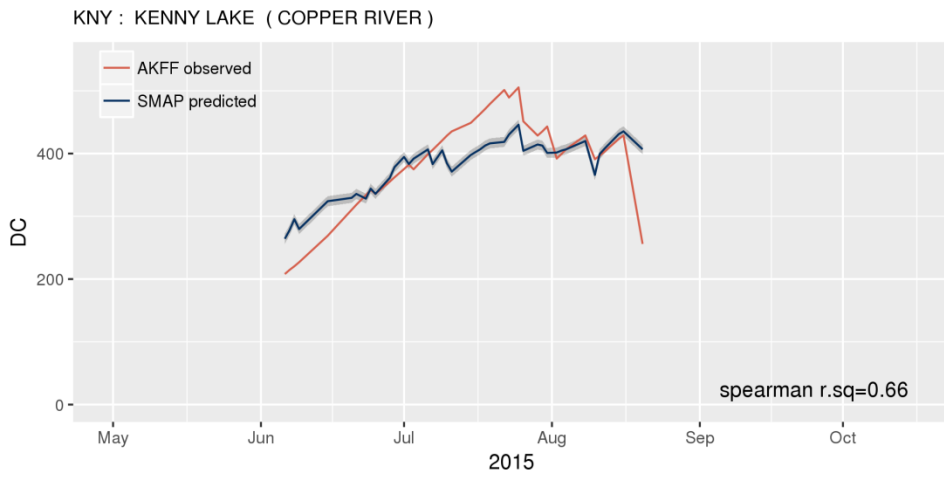

KAVA2 : KAVET CREEK (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.79

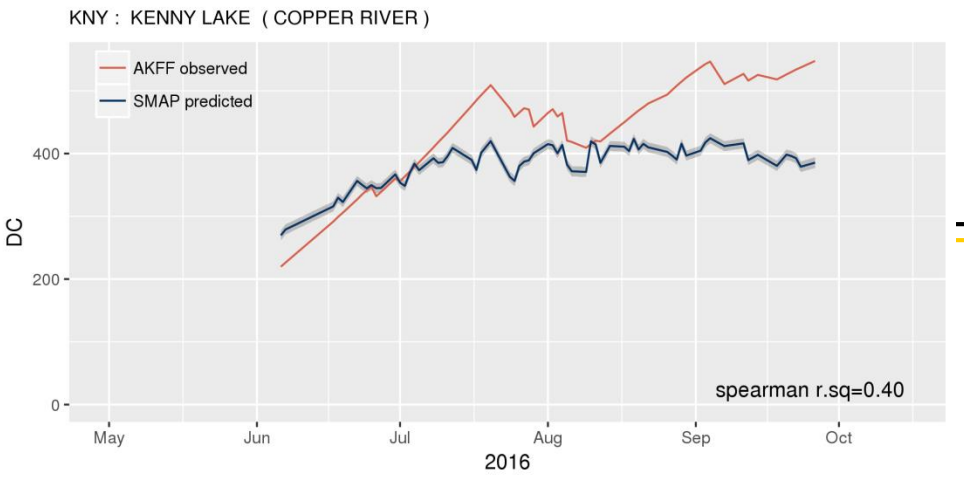

KELA2 : KELLY (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.81

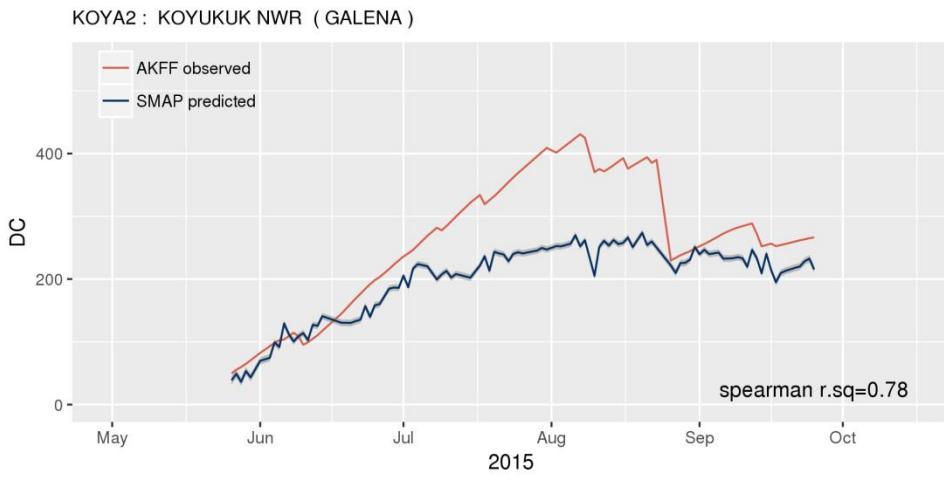

KELA2 : KELLY (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.87

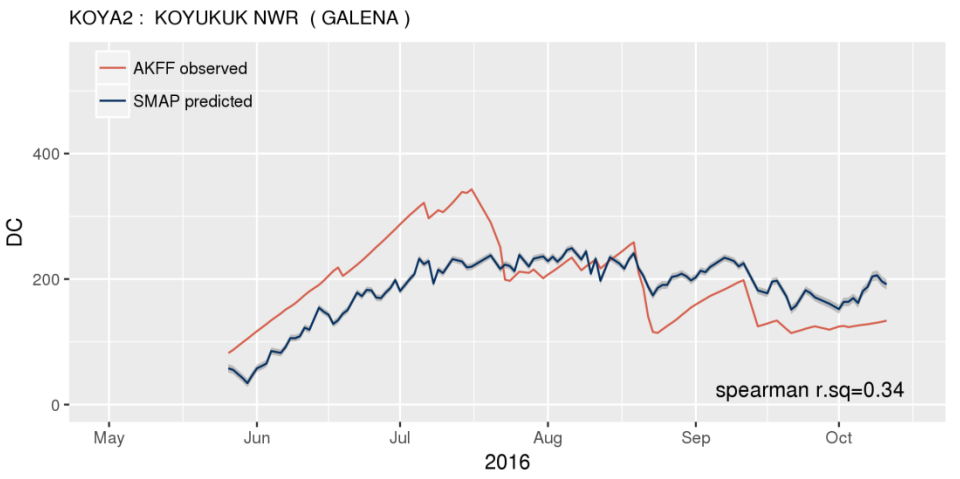

KLAA2 : KLAWASI (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.39

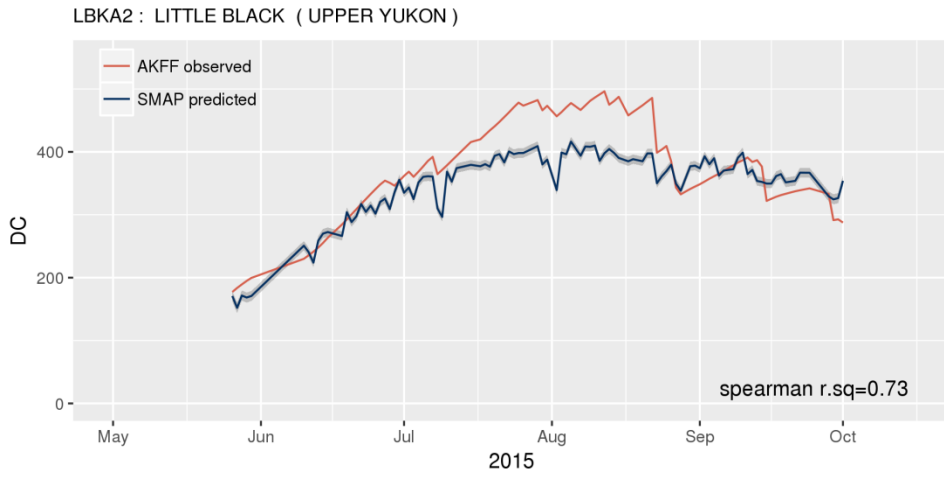

KLAA2 : KLAWASI (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.45

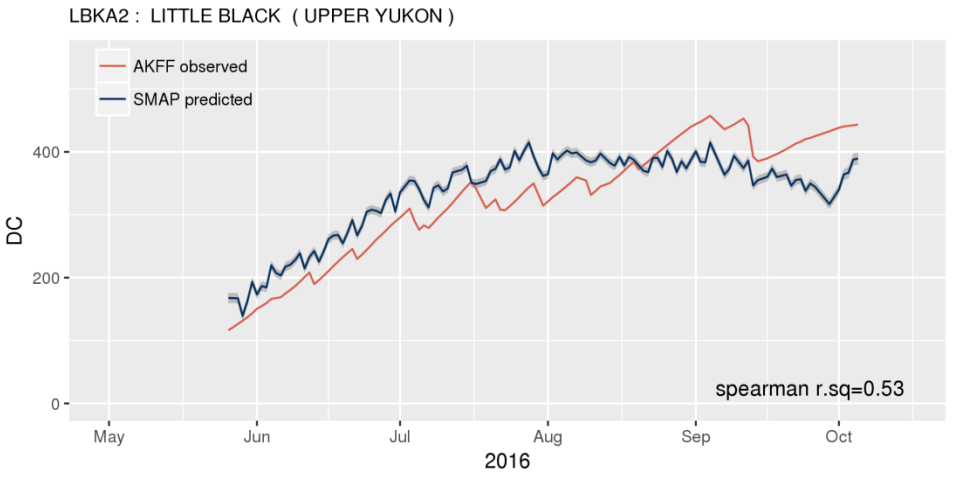

KNY : KENNY LAKE (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.66

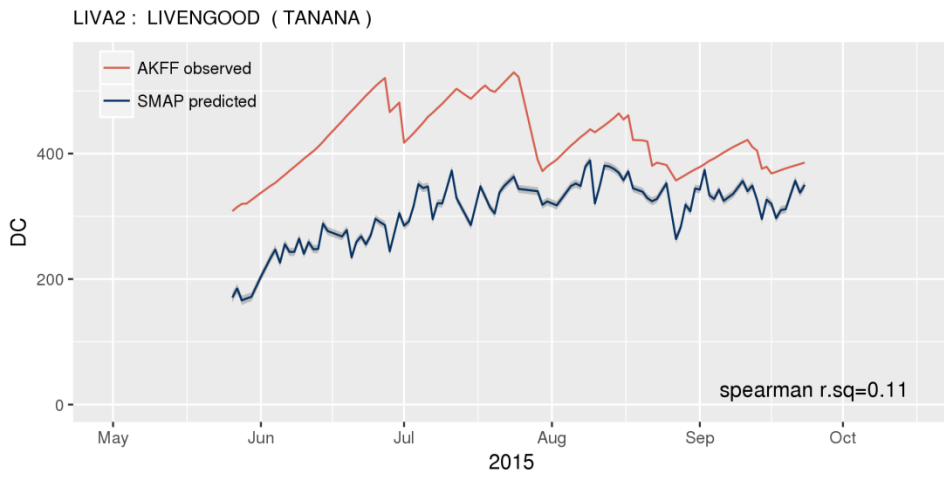

KNY : KENNY LAKE (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.40

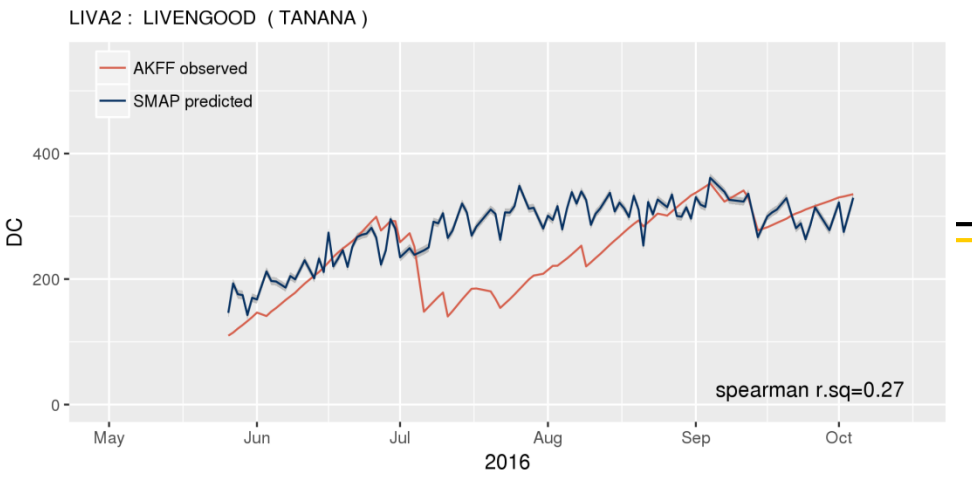

KOYA2 : KOYUKUK NWR (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.78

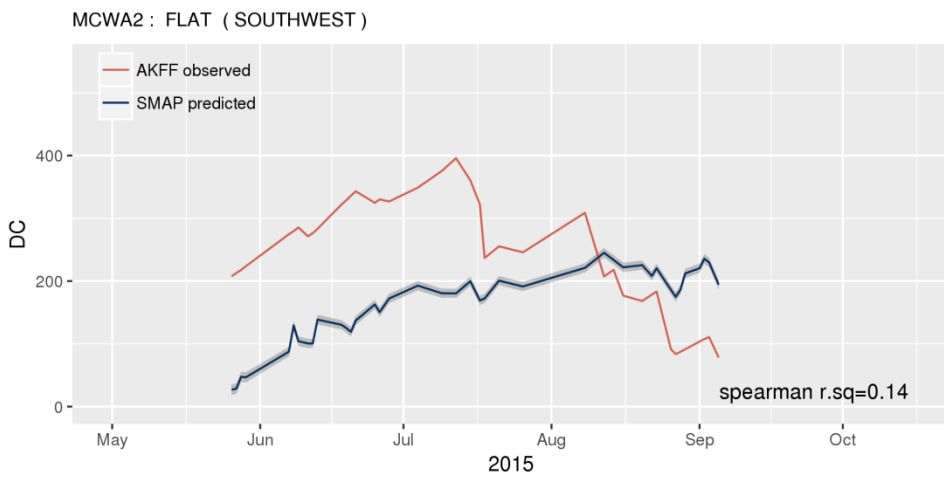

KOYA2 : KOYUKUK NWR (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.34

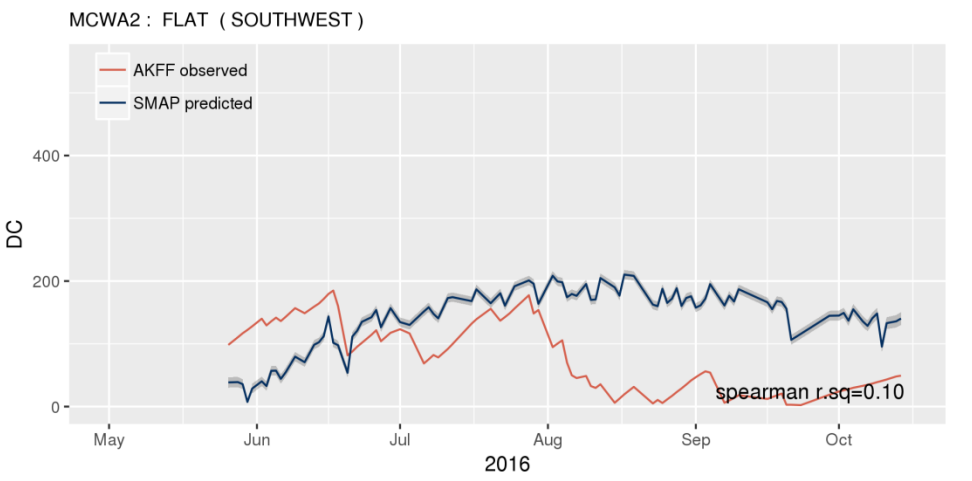

LBKA2 : LITTLE BLACK (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.73

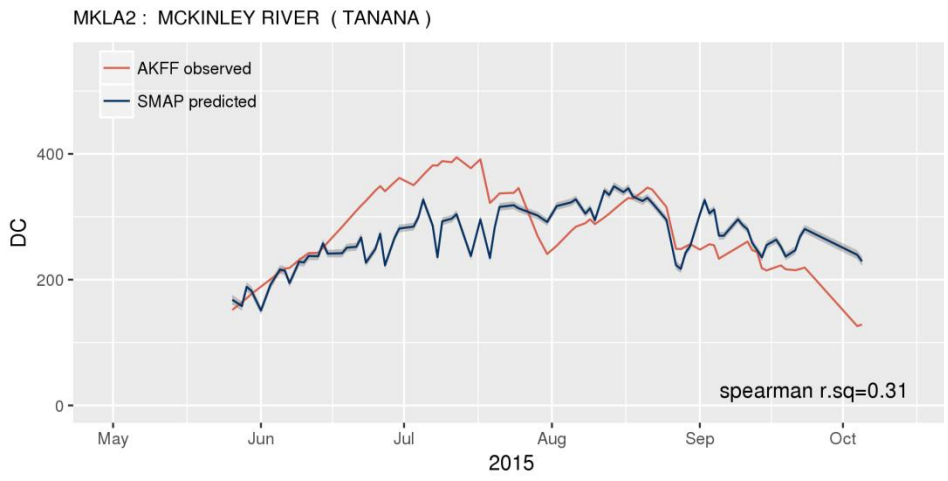

LBKA2 : LITTLE BLACK (UPPER YUKON)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.53

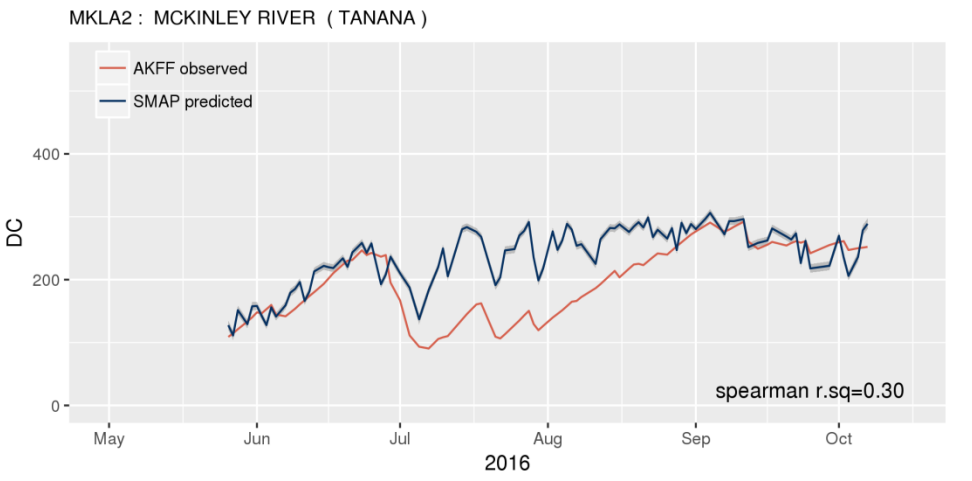

LIVA2 : LIVENGOOD (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.11


LIVA2 : LIVENGOOD (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.27

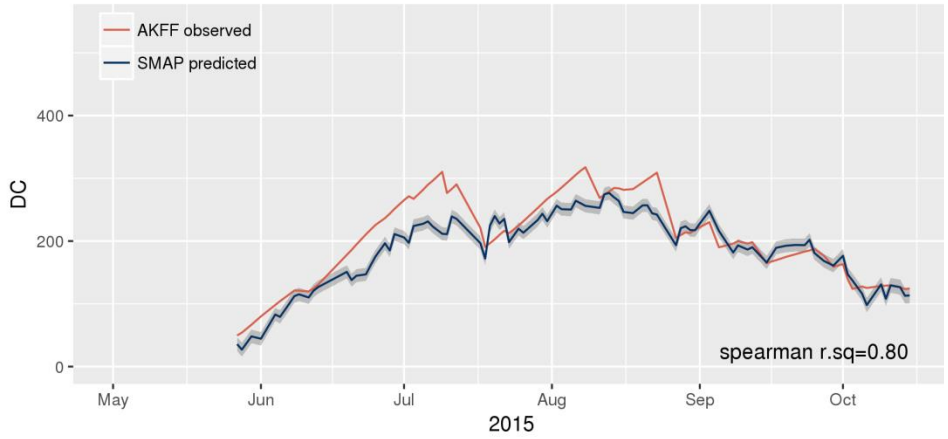

MCWA2 : FLAT (SOUTHWEST)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.14


MCWA2 : FLAT (SOUTHWEST)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.10

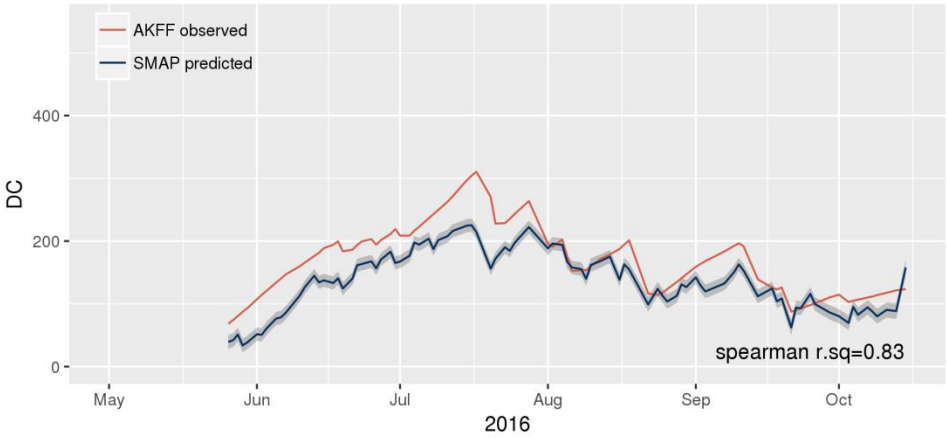

MKLA2 : MCKINLEY RIVER (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.31


MKLA2 : MCKINLEY RIVER (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.30

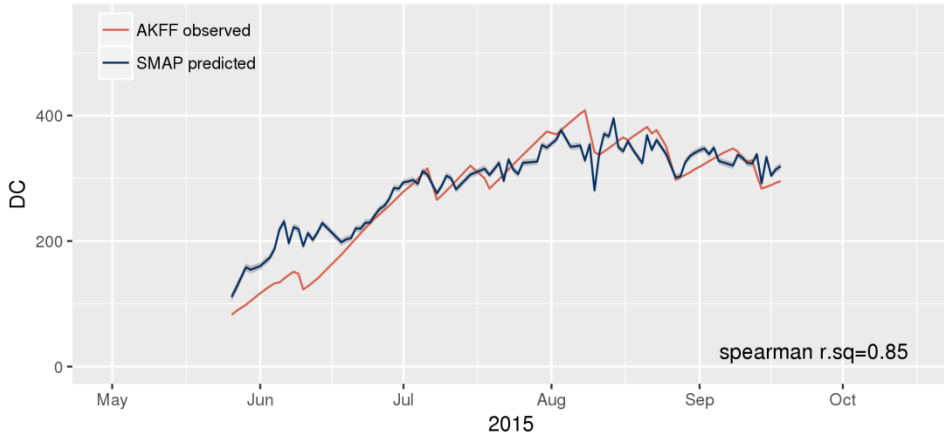
NKOA2 : INNOKO FLATS (GALENA)



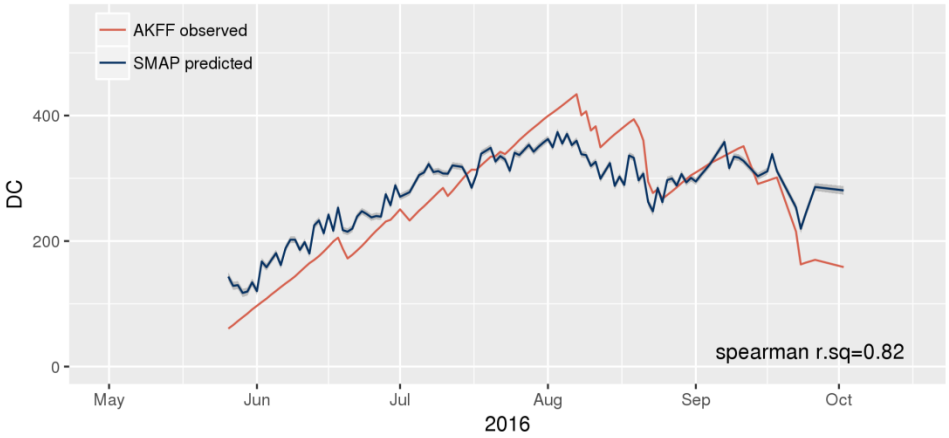
NKOA2 : INNOKO FLATS (GALENA)



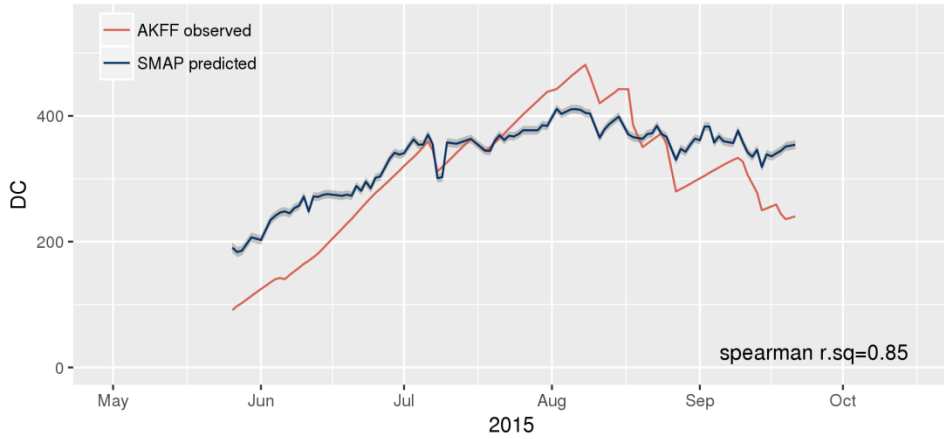
NRUA2 : NORUTAK LAKE (TANANA)



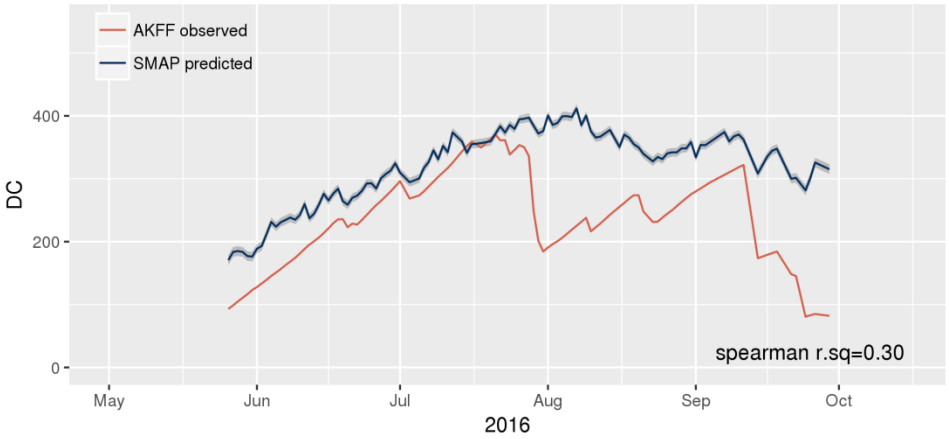
NRUA2 : NORUTAK LAKE (TANANA)

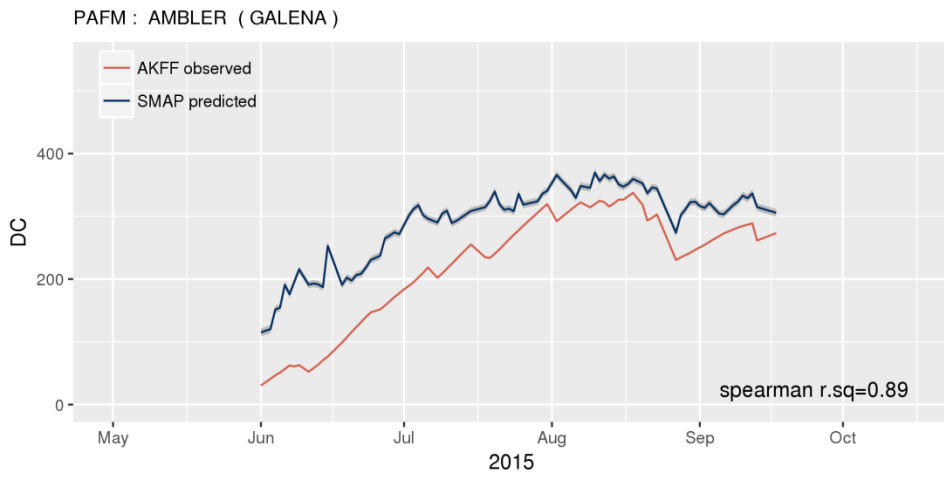


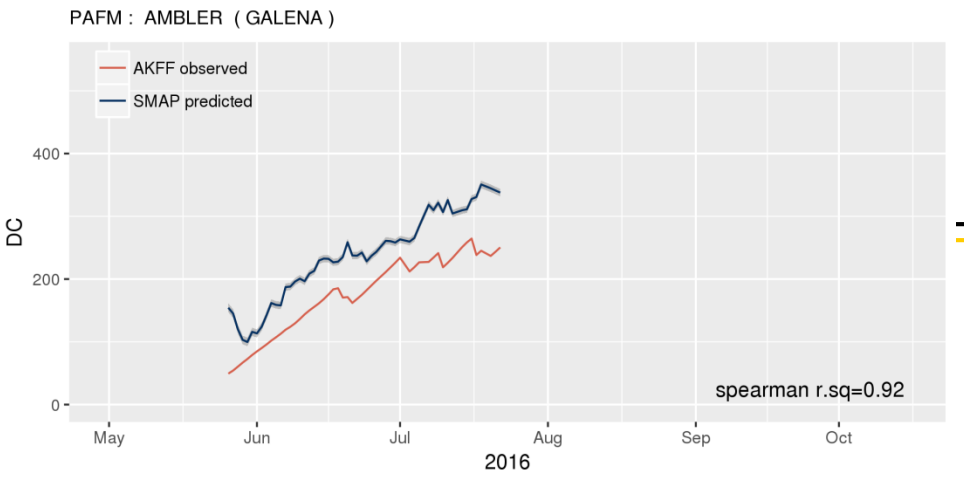
PABT : BETTLES (TANANA)

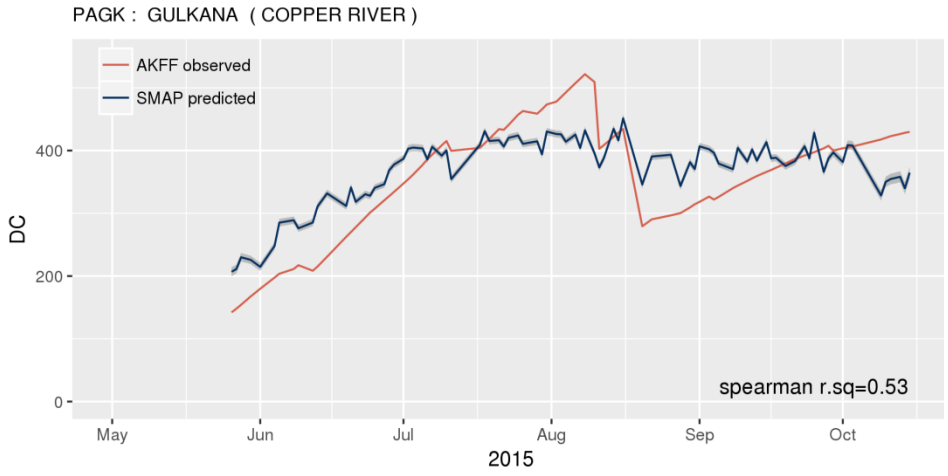


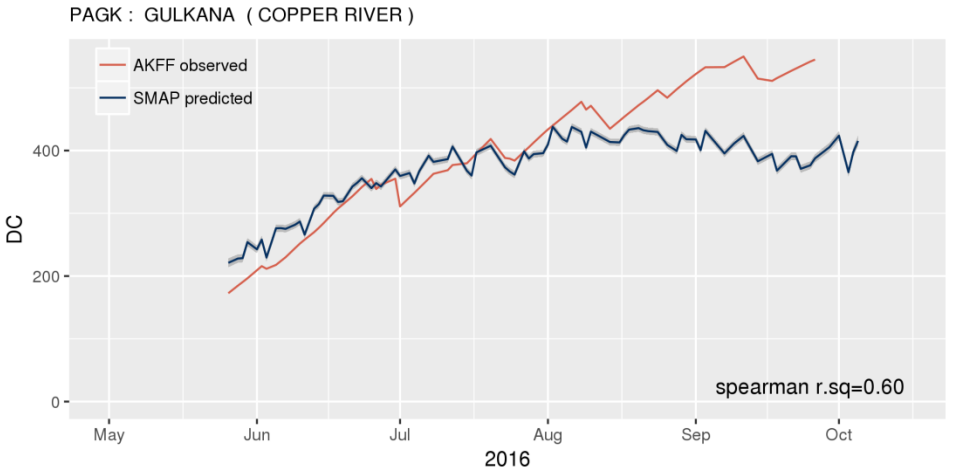
PABT : BETTLES (TANANA)

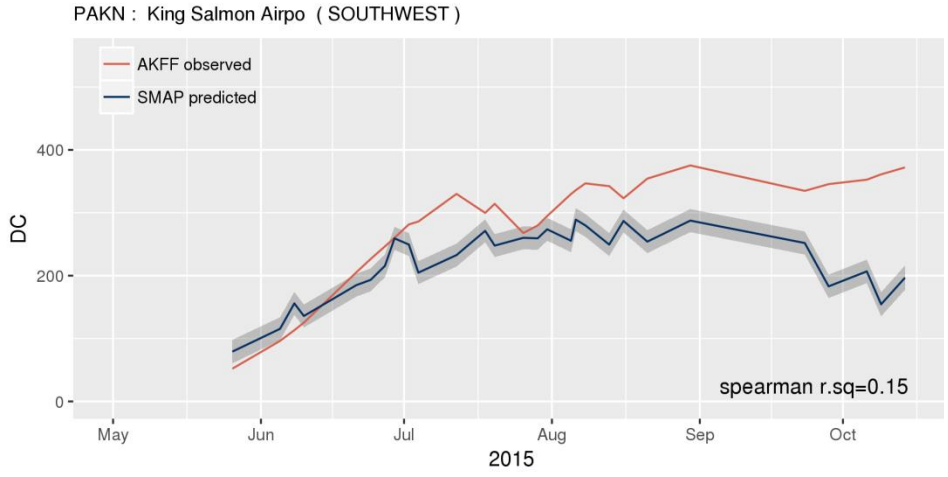


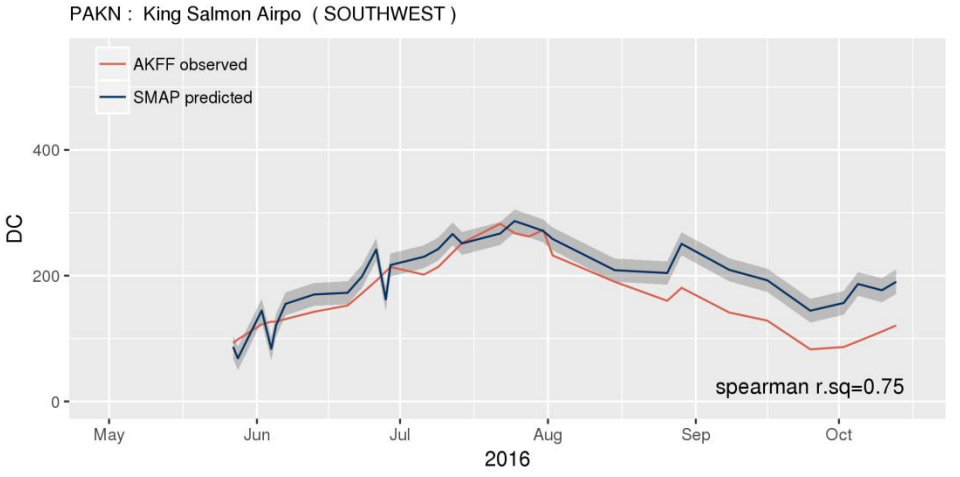

PAFM : AMBLER (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.89


PAFM : AMBLER (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.92

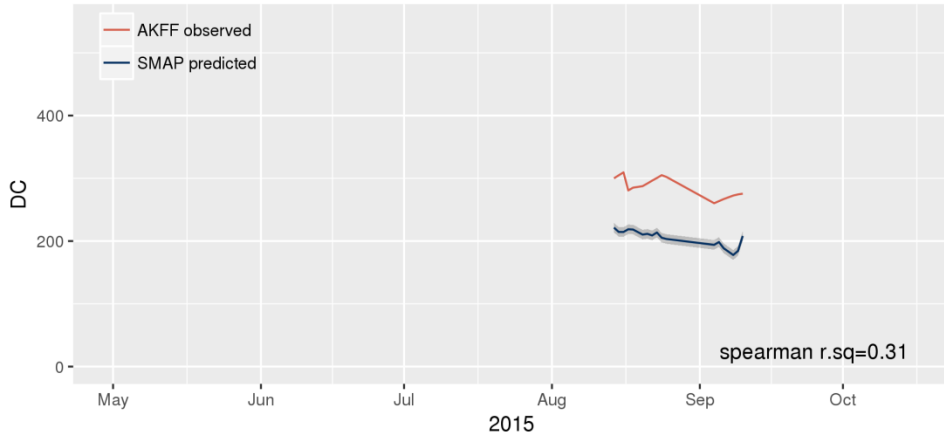

PAGK : GULKANA (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.53


PAGK : GULKANA (COPPER RIVER)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.60

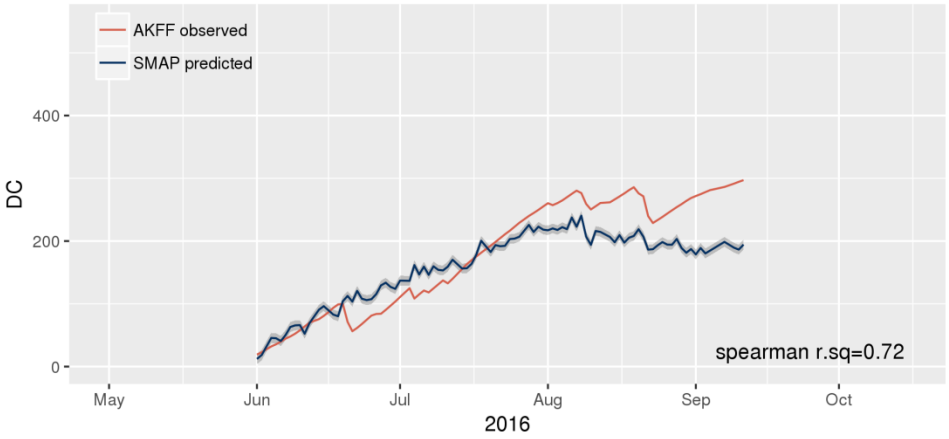

PAKN : King Salmon Airpo (SOUTHWEST)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.15


PAKN : King Salmon Airpo (SOUTHWEST)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.75

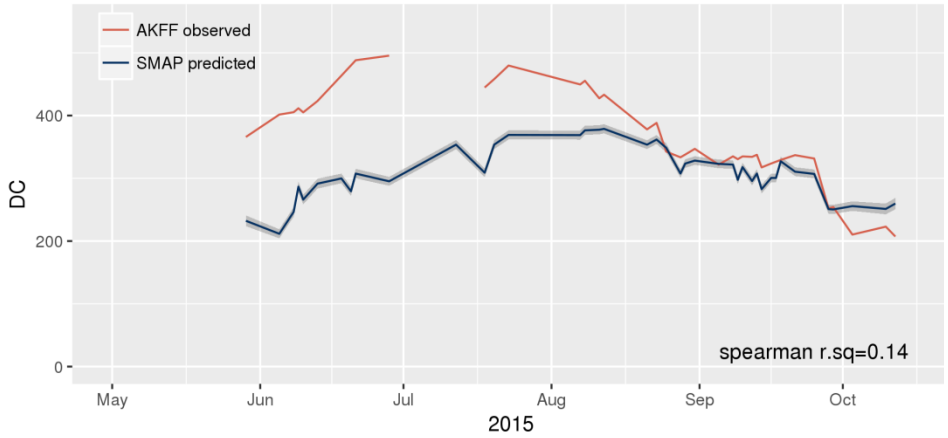
PAMA2 : PAMICHTUK LAKE (TANANA)



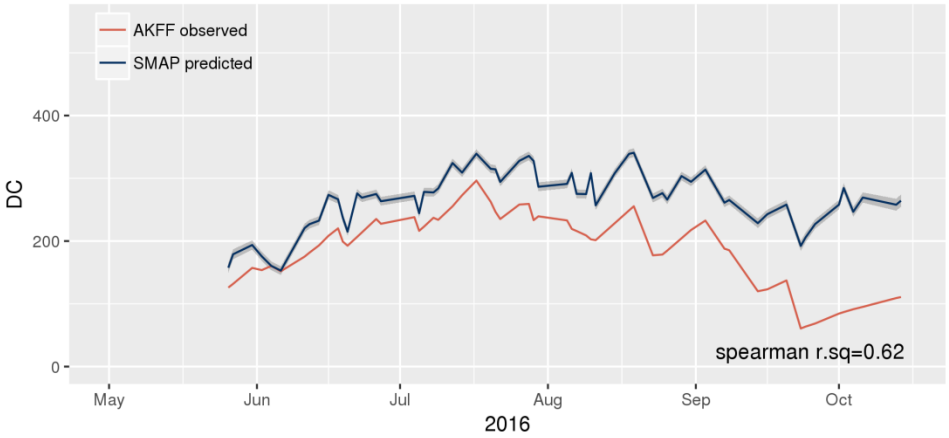
PAMA2 : PAMICHTUK LAKE (TANANA)



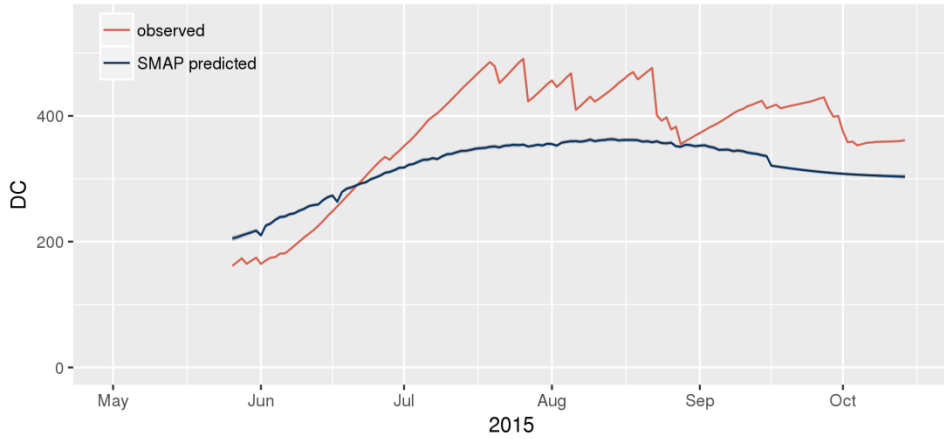
PAMC : MCGRATH (SOUTHWEST)



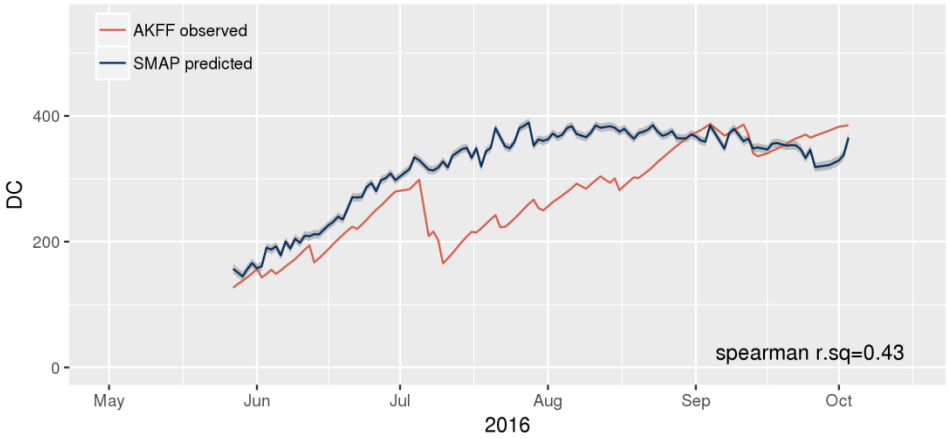
PAMC : MCGRATH (SOUTHWEST)



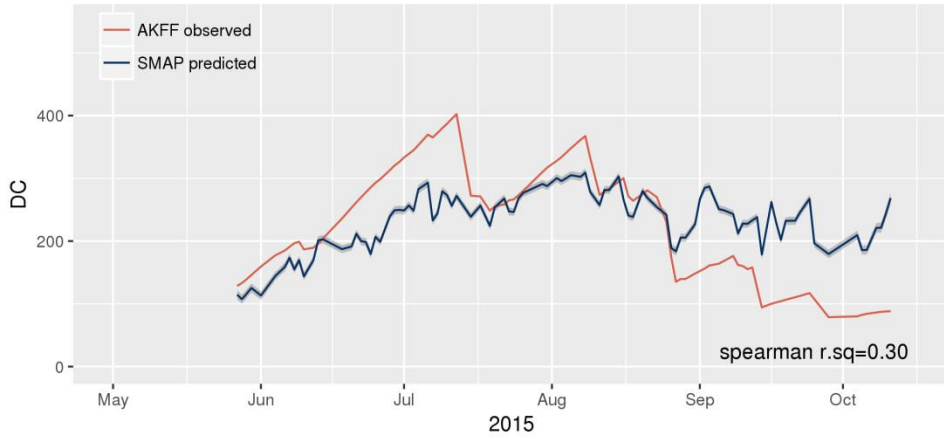
PCKA2 : PREACHER CREEK (3 TAIGA)



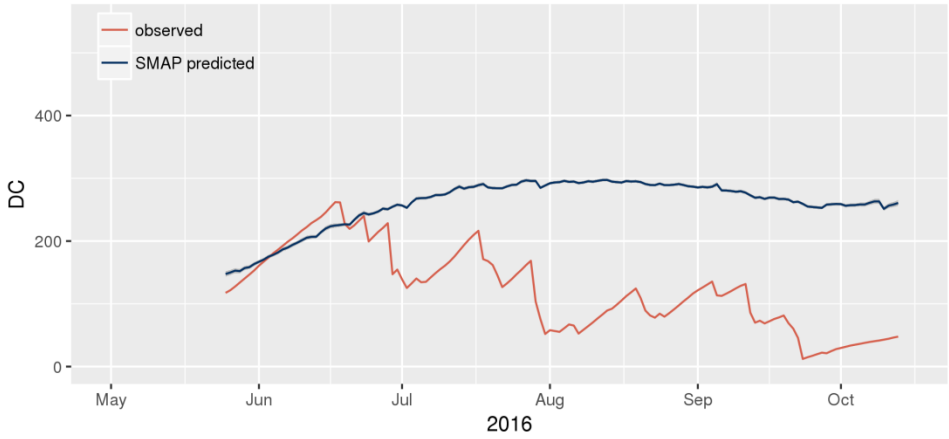
PCKA2 : PREACHER CREEK (UPPER YUKON)



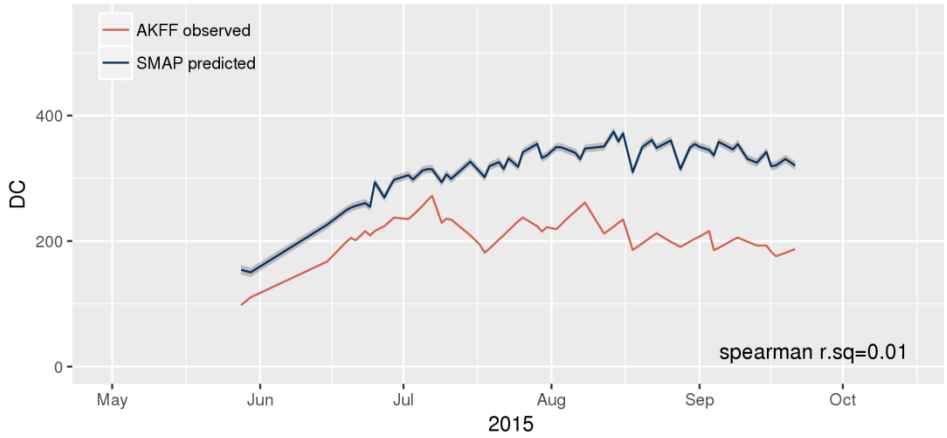
PMNA2 : POORMAN (TANANA)



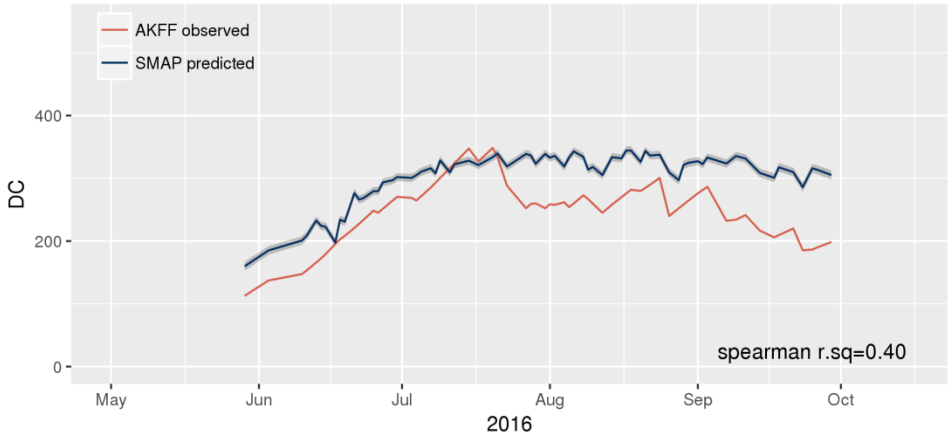
PMNA2 : POORMAN (3 TAIGA)



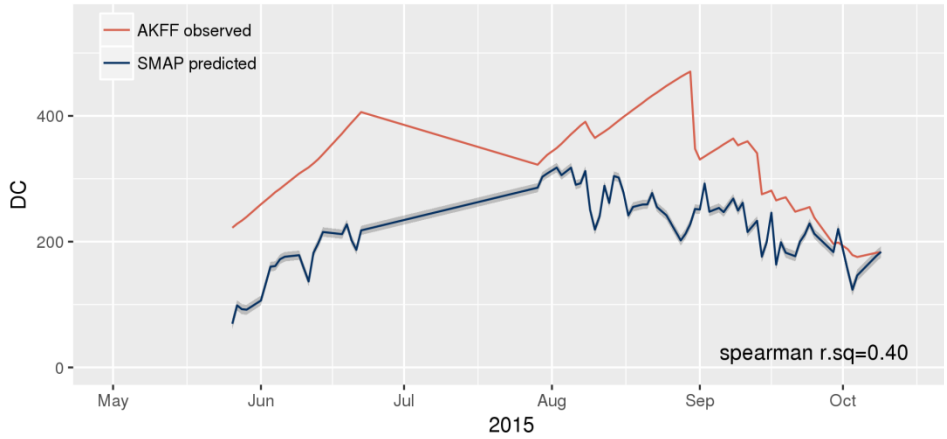
PXKA2 : PAXSON (COPPER RIVER)



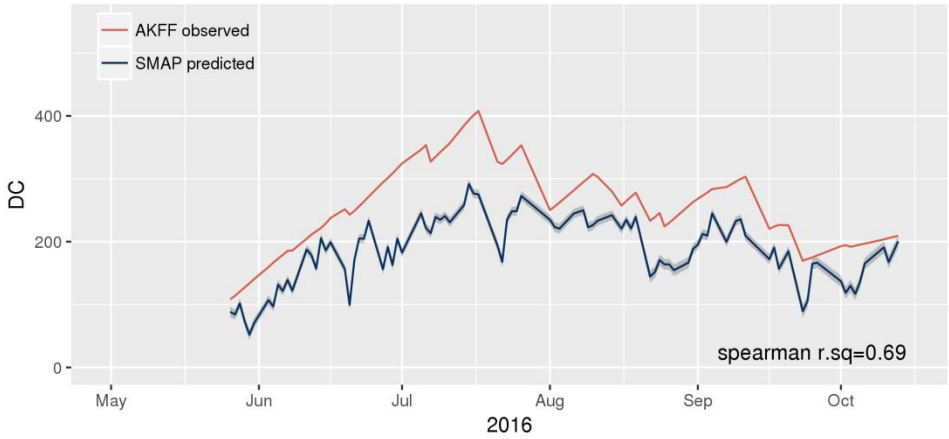
PXKA2 : PAXSON (COPPER RIVER)

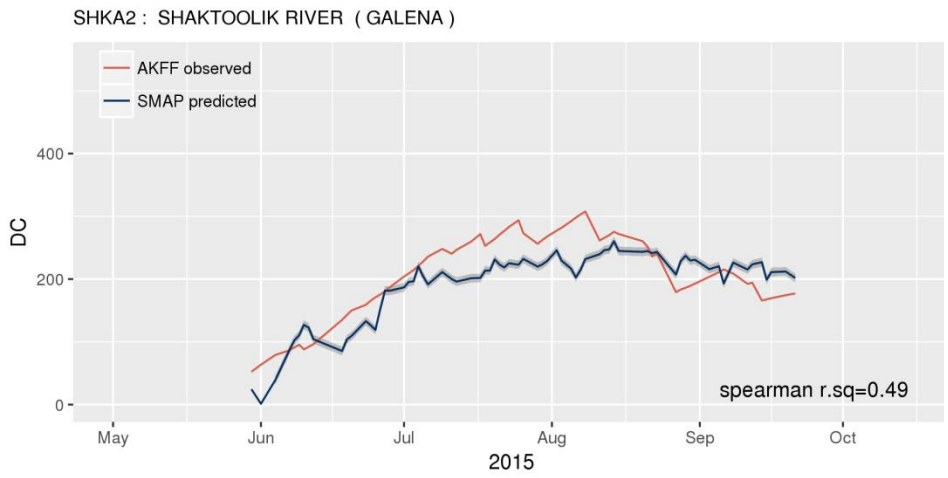


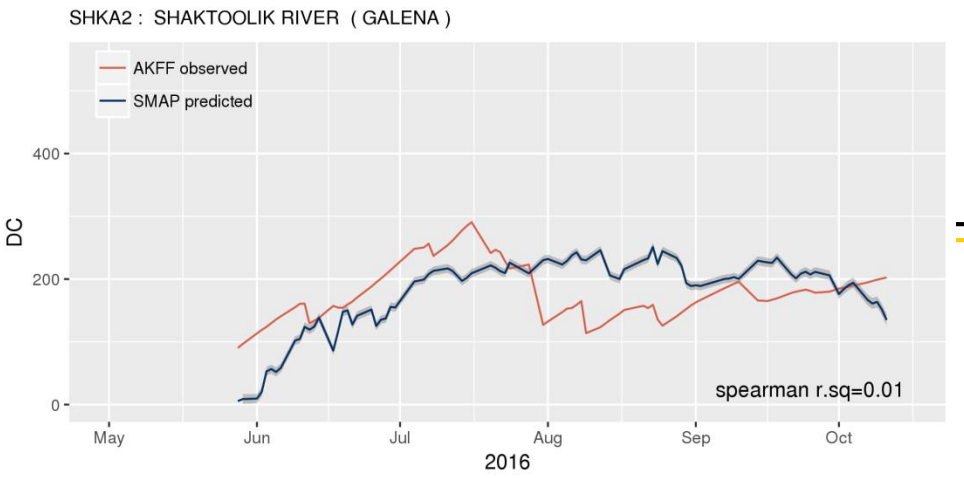
RNDA2 : ROUND LAKE (TANANA)

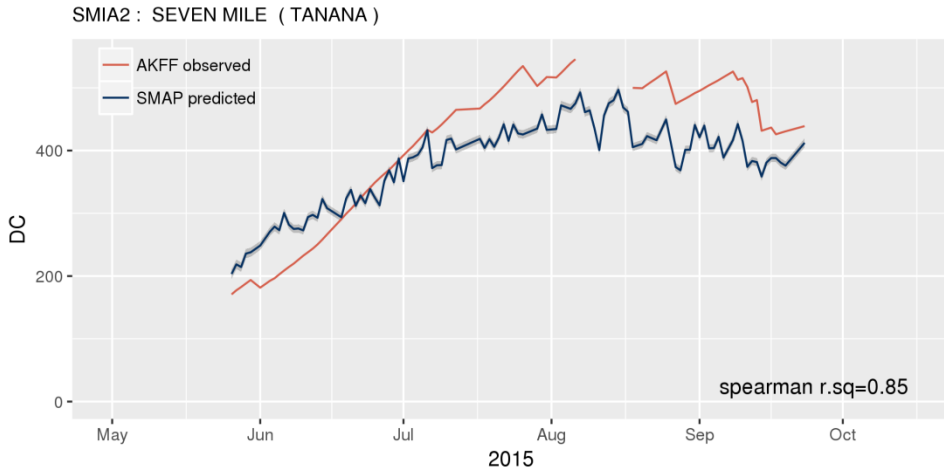


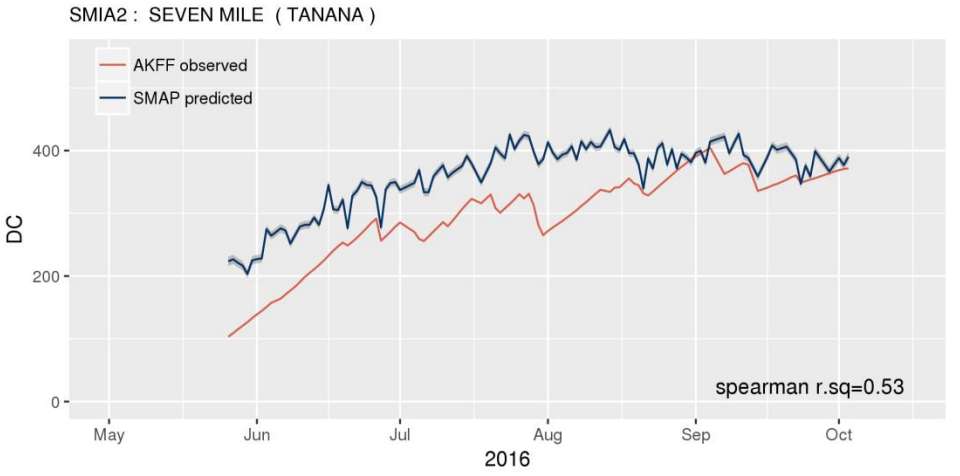
RNDA2 : ROUND LAKE (TANANA)

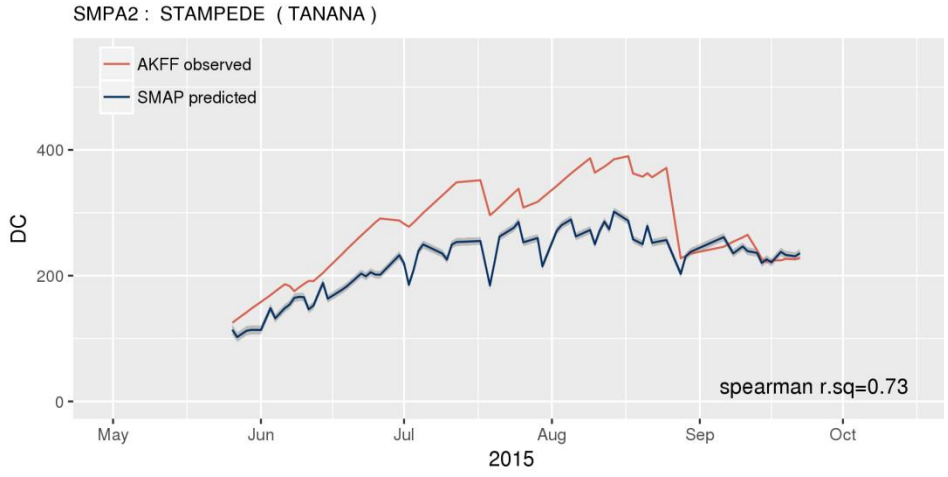


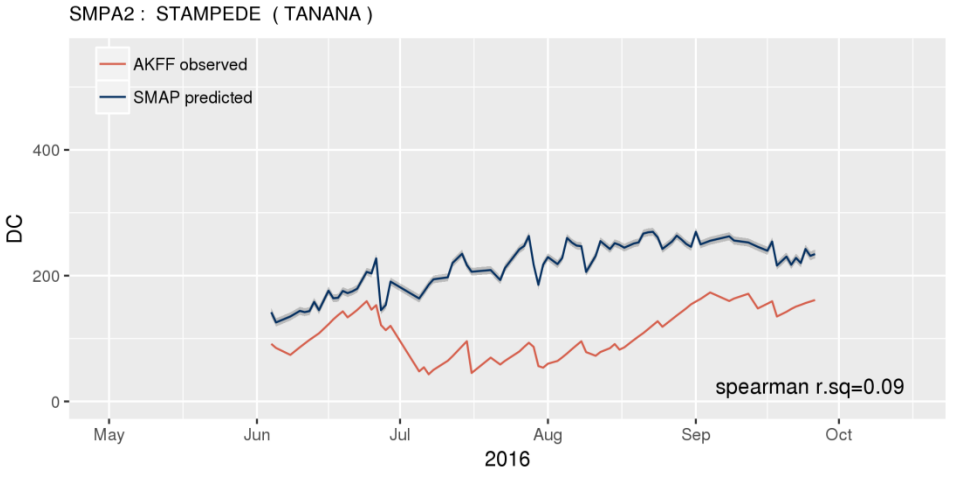

SHKA2 : SHAKTOOLIK RIVER (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.49


SHKA2 : SHAKTOOLIK RIVER (GALENA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.01


SMIA2 : SEVEN MILE (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.85

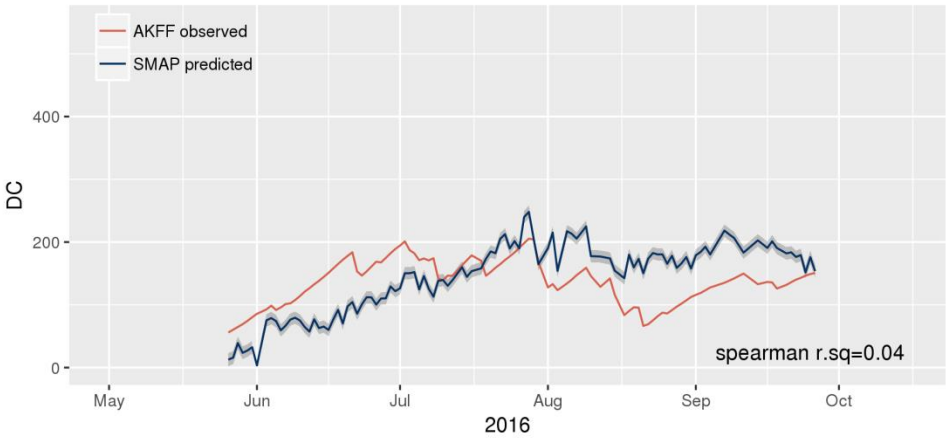

SMIA2 : SEVEN MILE (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.53


SMPA2 : STAMPEDE (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.73

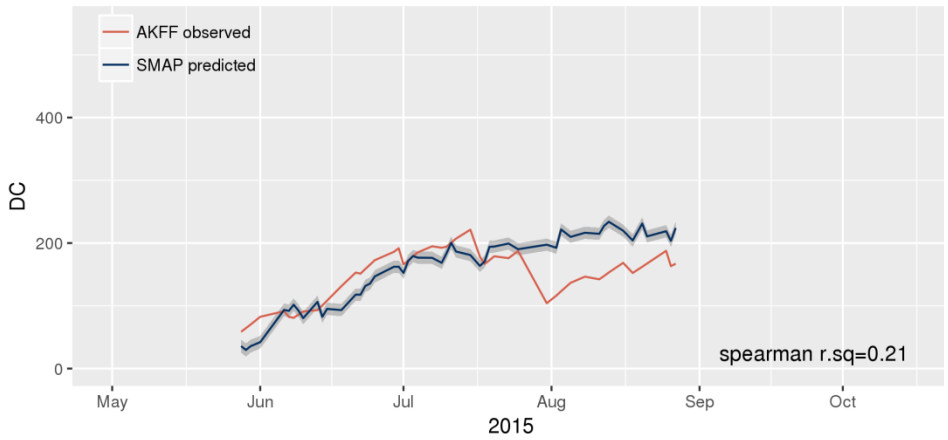

SMPA2 : STAMPEDE (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.09

SMTA2 : SALMON TROUT (UPPER YUKON)

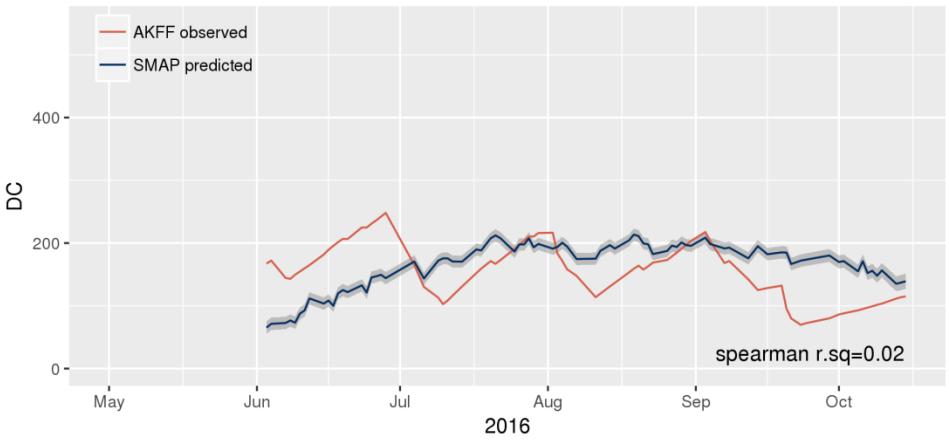
SMTA2 : SALMON TROUT (UPPER YUKON)



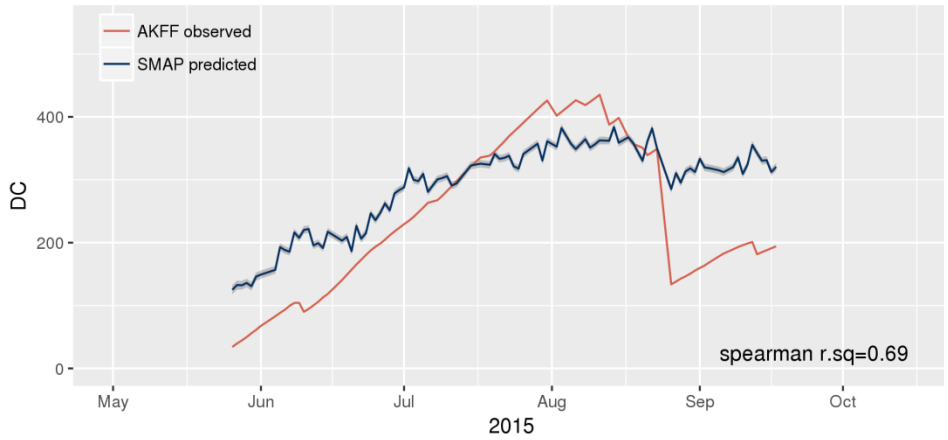
SNIA2 : SNIPE LAKE (SOUTHWEST)



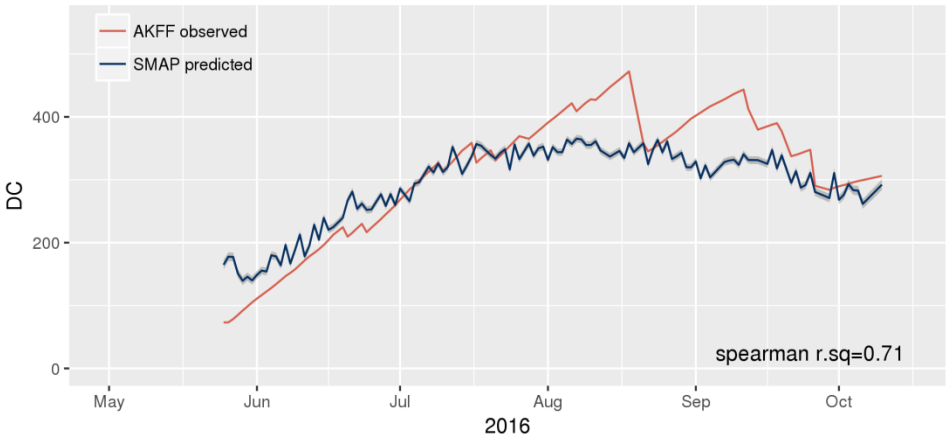
SNIA2 : SNIPE LAKE (SOUTHWEST)



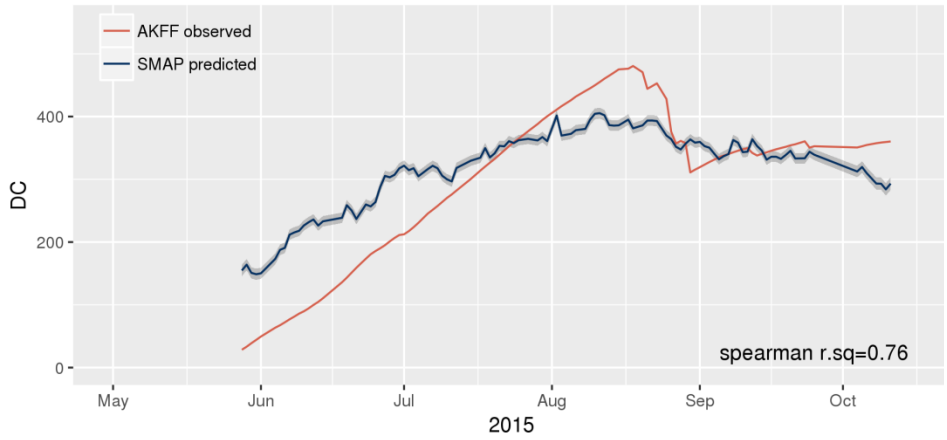
SRKA2 : KIANA (GALENA)



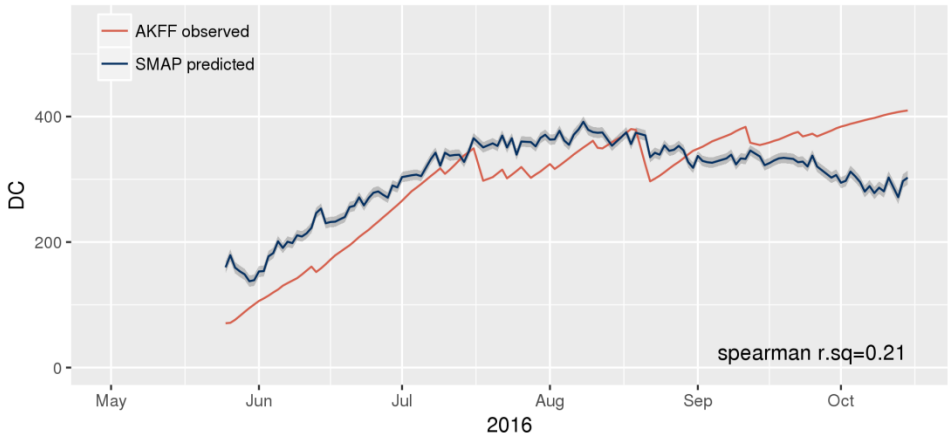
SRKA2 : KIANA (GALENA)



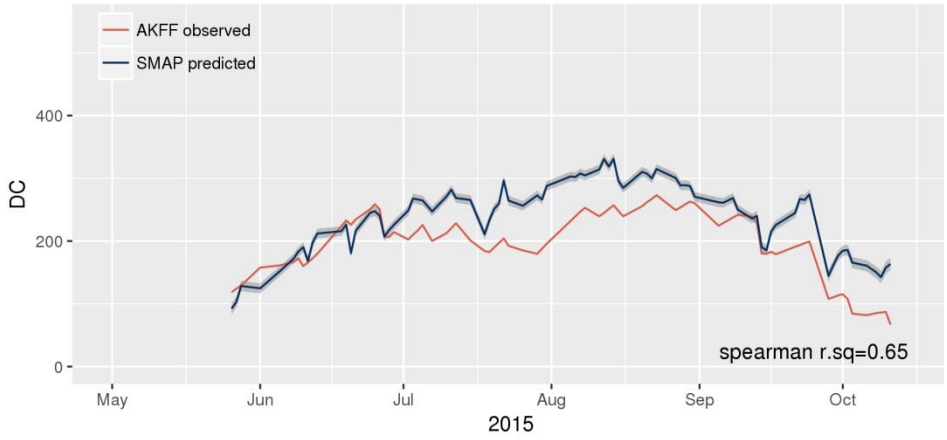
SRTA2 : SERPENTINE (GALENA)



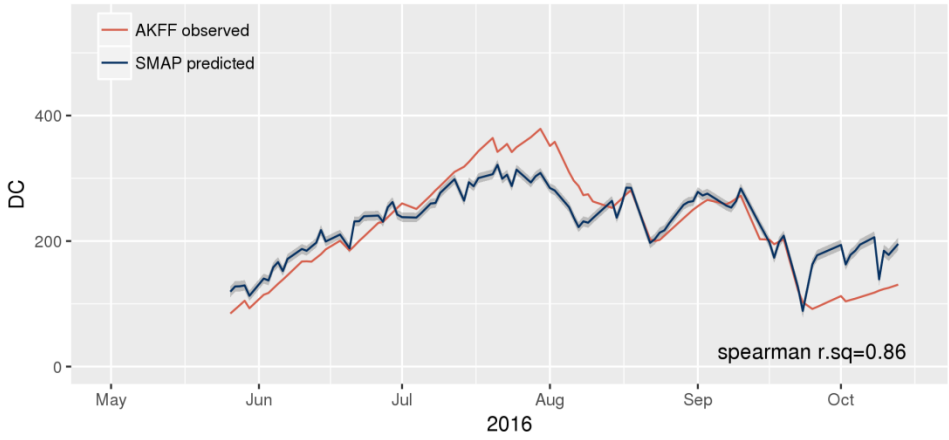
SRTA2 : SERPENTINE (GALENA)



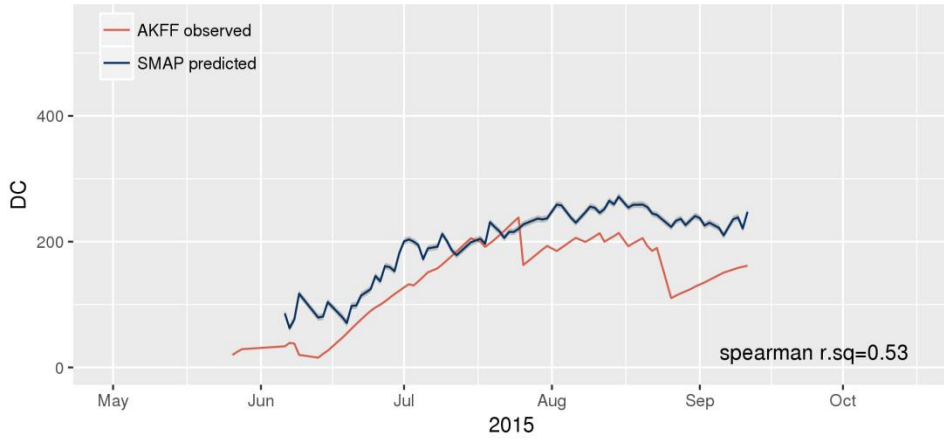
SRVA2 : STONEY RIVER (SOUTHWEST)



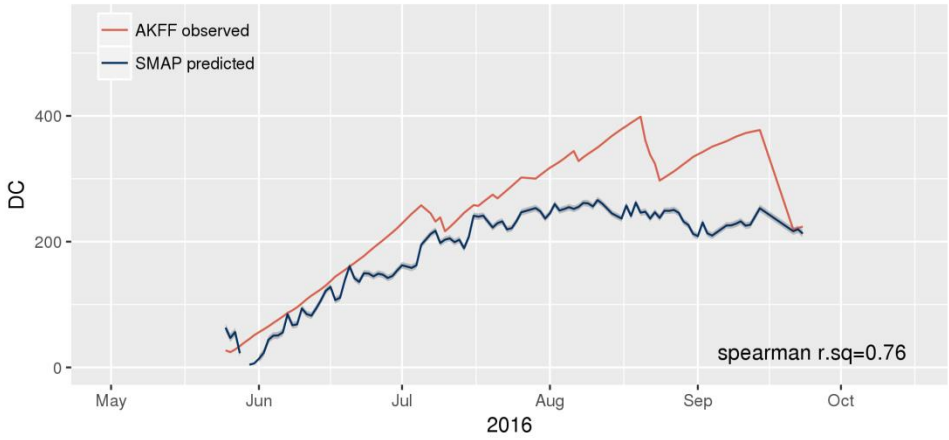
SRVA2 : STONEY RIVER (SOUTHWEST)



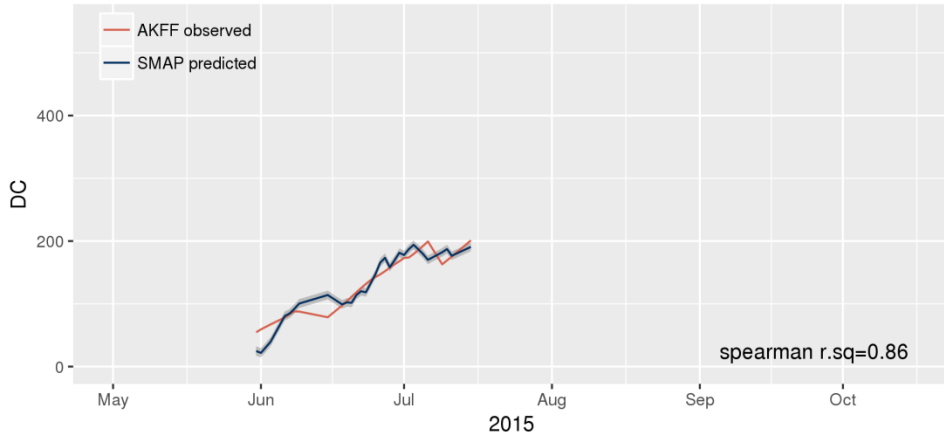
SRWA2 : SALMON RIVER (GALENA)



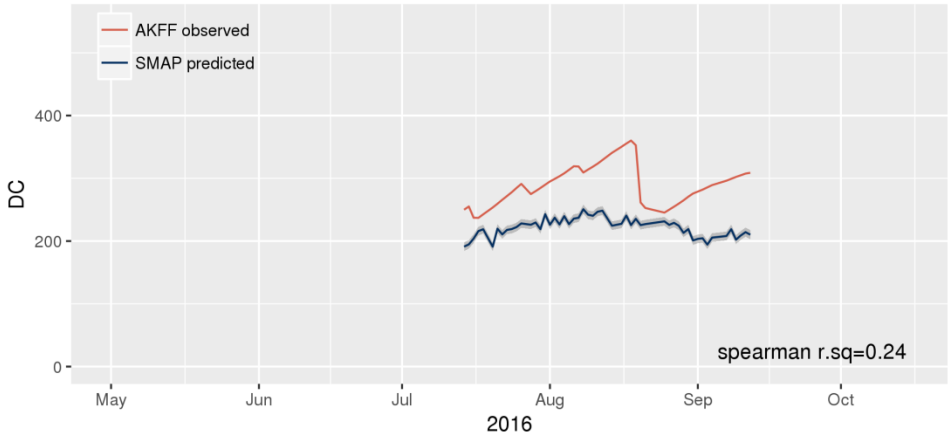
SRWA2 : SALMON RIVER (GALENA)



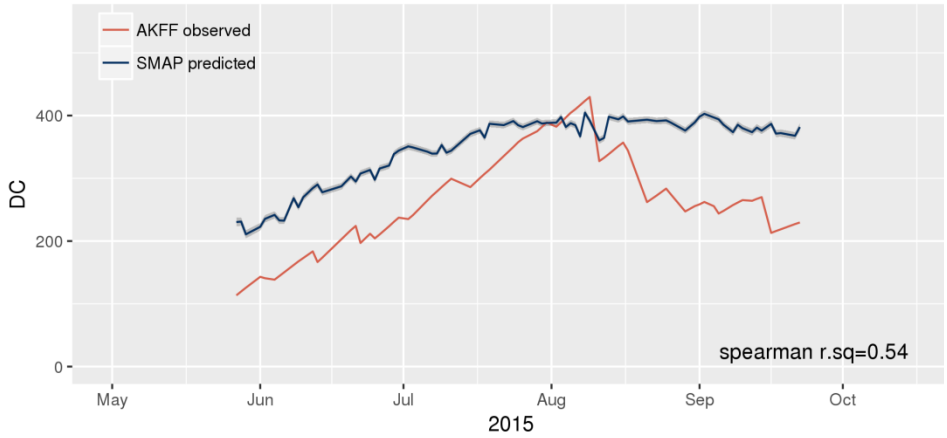
SSIA2 : SISIAK (GALENA)



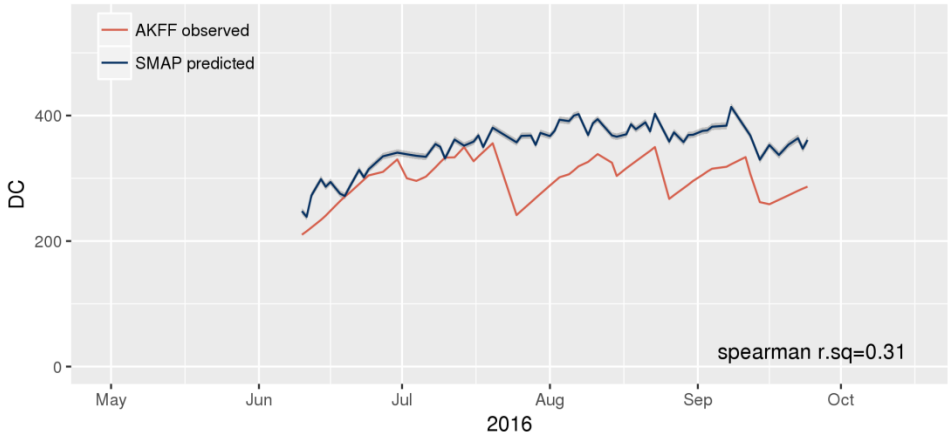
SSIA2 : SISIAK (GALENA)



SSZ : SLANA (COPPER RIVER)

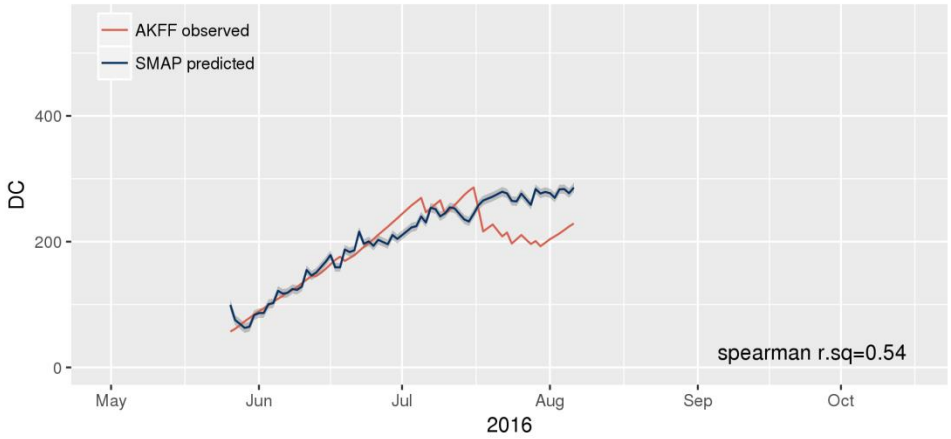


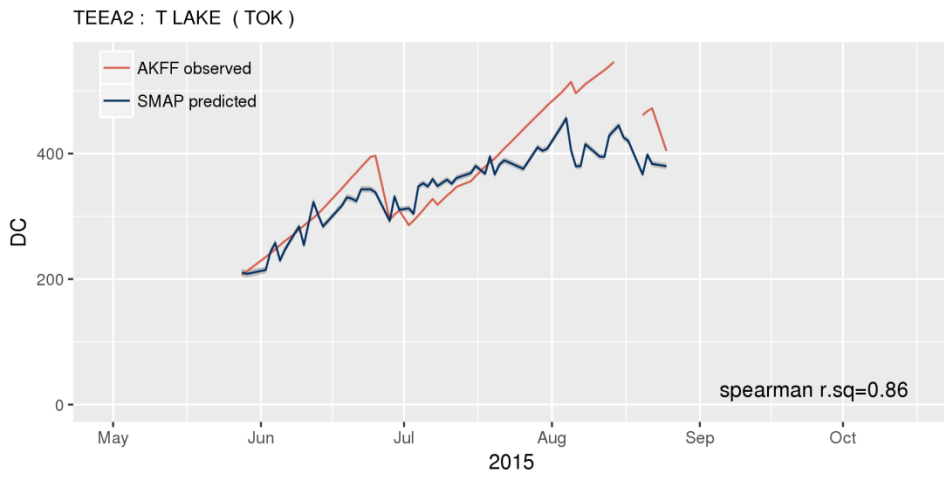
SSZ : SLANA (COPPER RIVER)

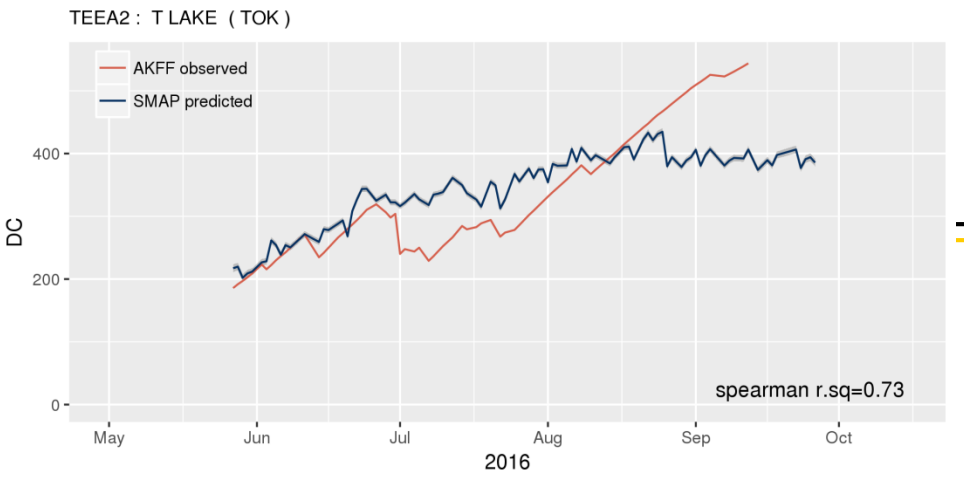


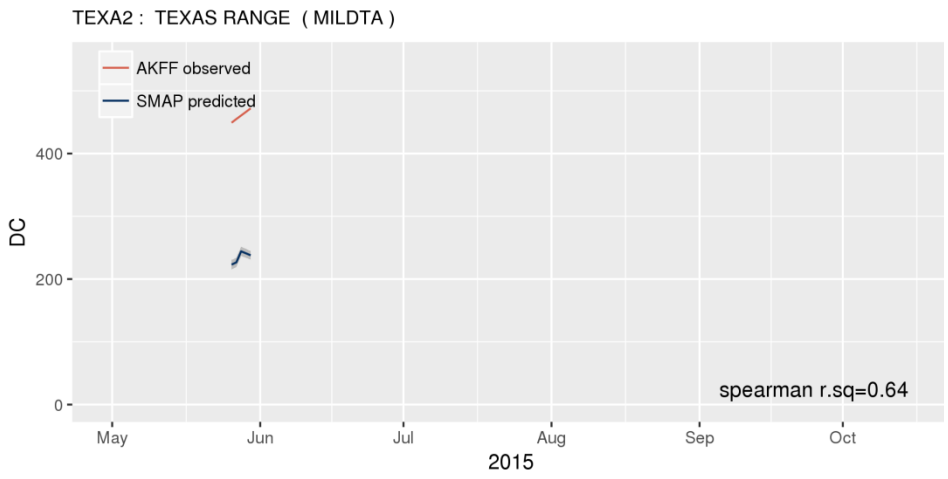
TAGA2 : TAG MTN (GALENA)

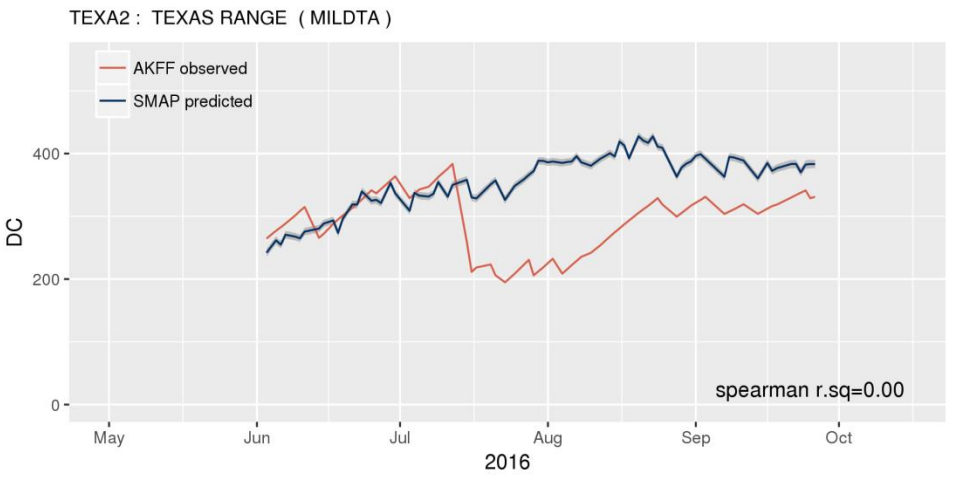
TAGA2 : TAG MTN (GALENA)

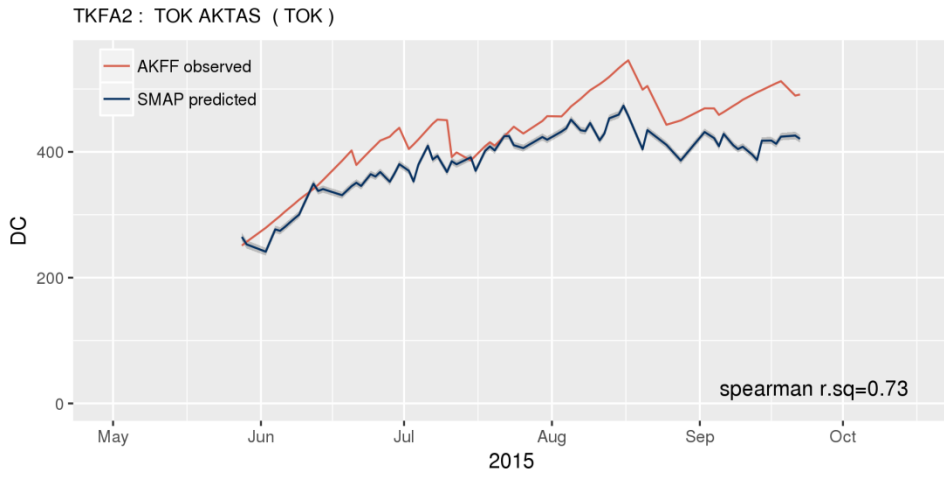


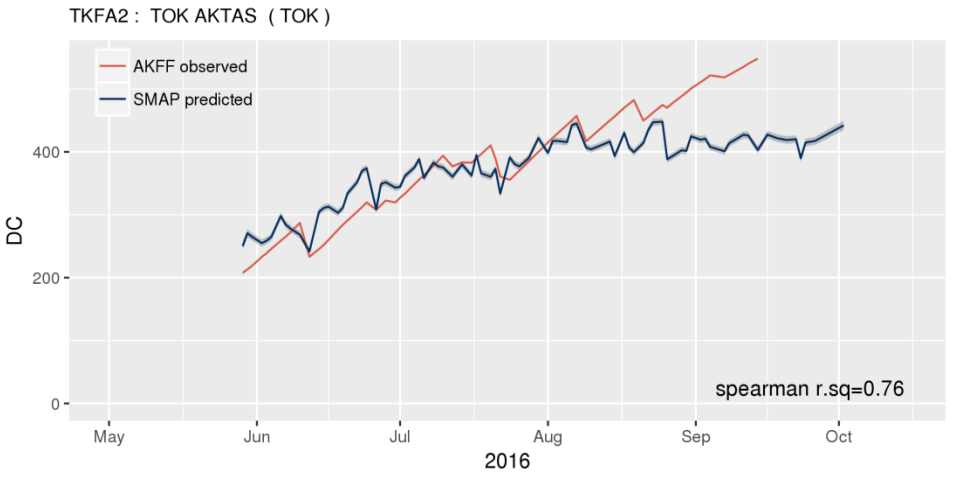

TEEA2 : T LAKE (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.86


TEEA2 : T LAKE (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.73

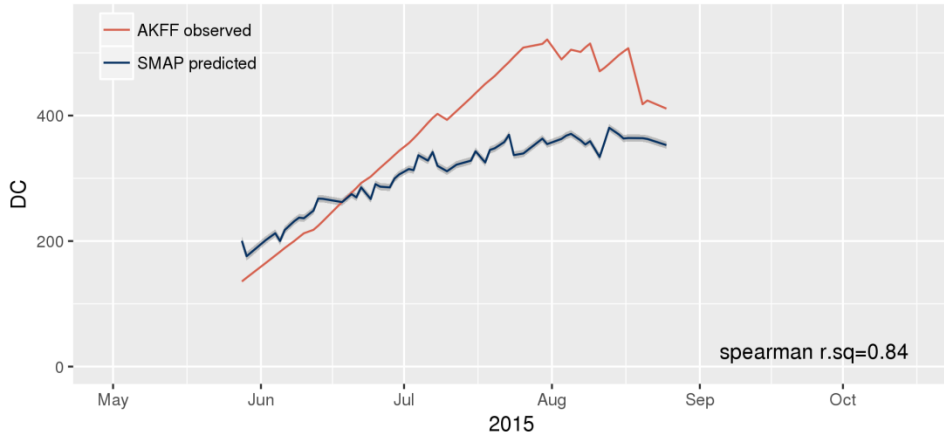

TEXA2 : TEXAS RANGE (MILDTA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.64


TEXA2 : TEXAS RANGE (MILDTA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.00

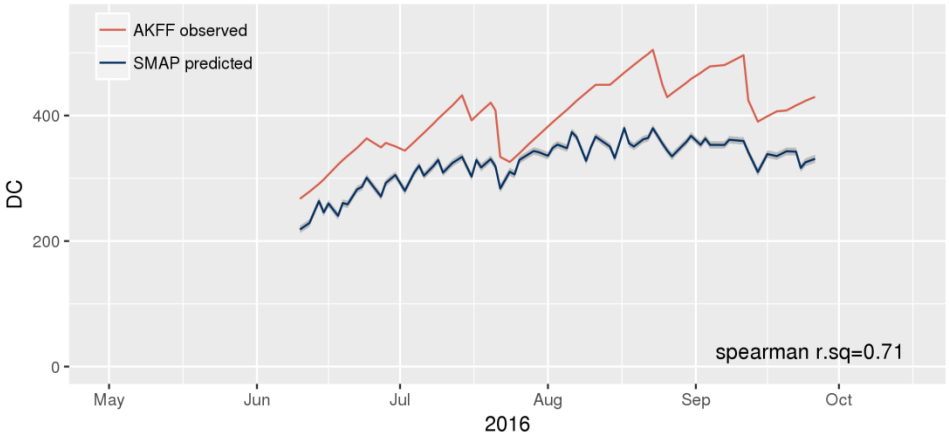

TKFA2 : TOK AKTAS (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.73


TKFA2 : TOK AKTAS (TOK)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.76

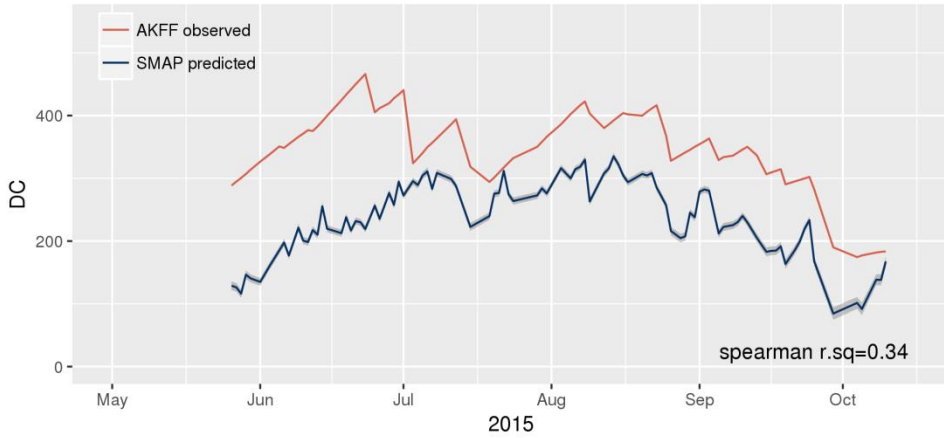
TKRA2 : TOK RIVER VALLEY (TOK)



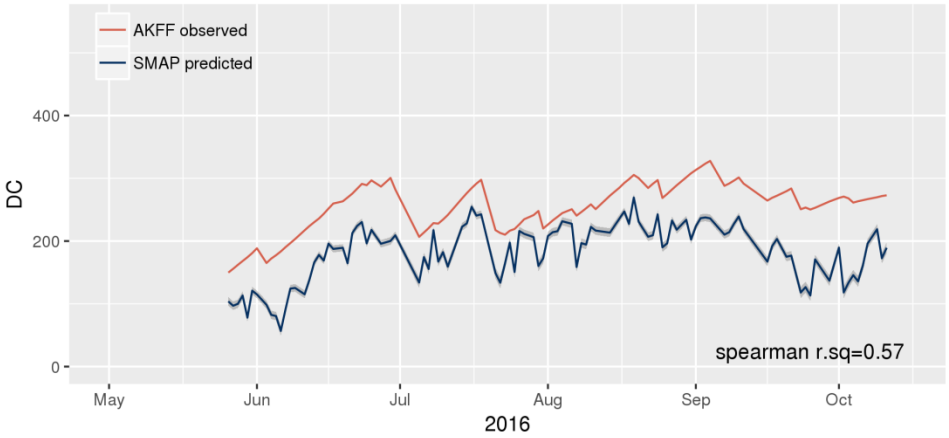
TKRA2 : TOK RIVER VALLEY (TOK)



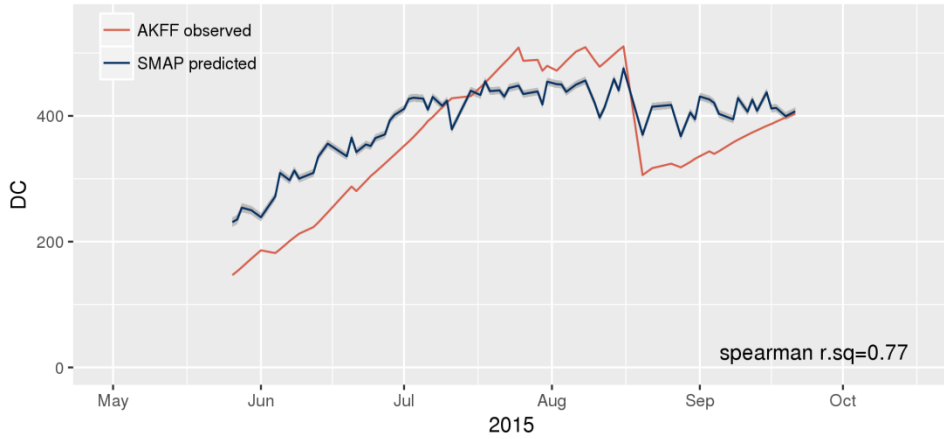
TLDA2 : TELIDA (SOUTHWEST)



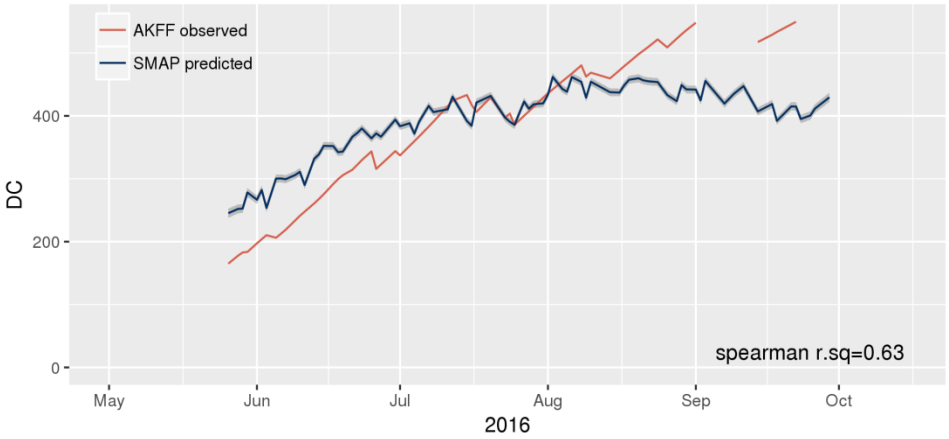
TLDA2 : TELIDA (SOUTHWEST)

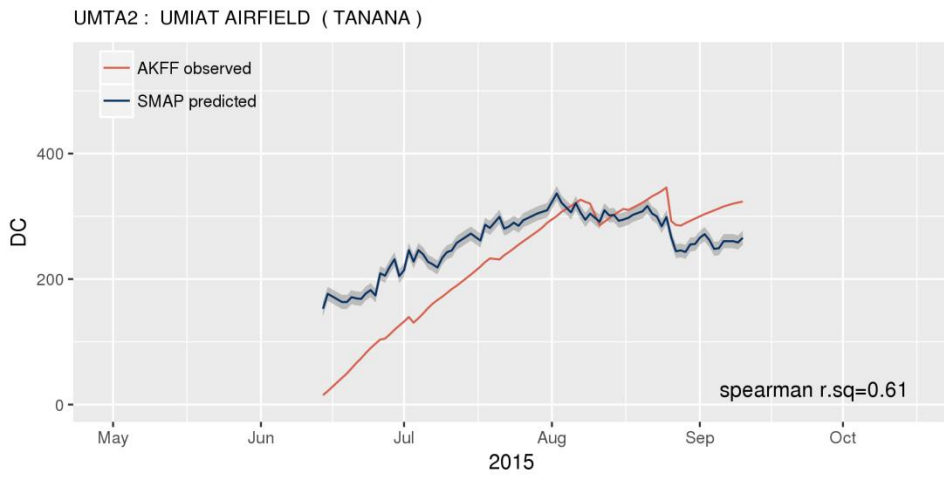


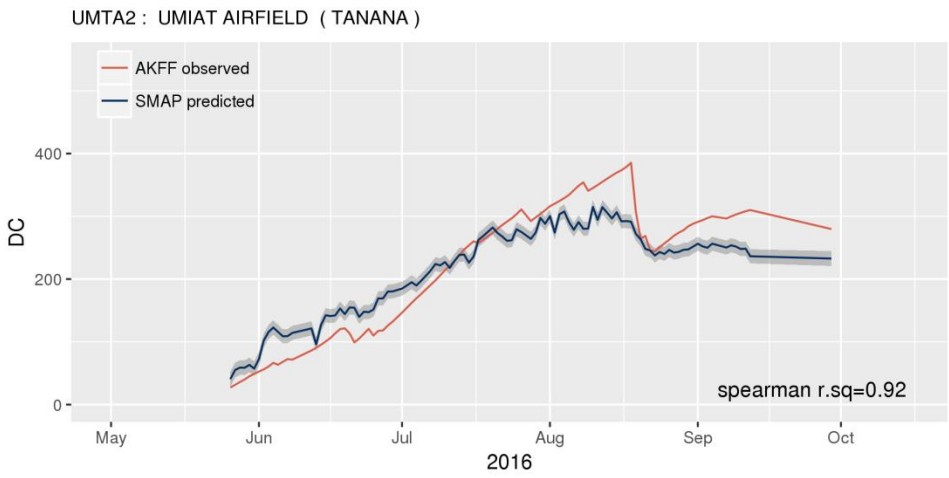
TZV : TAZLINA VILLAGE (COPPER RIVER)

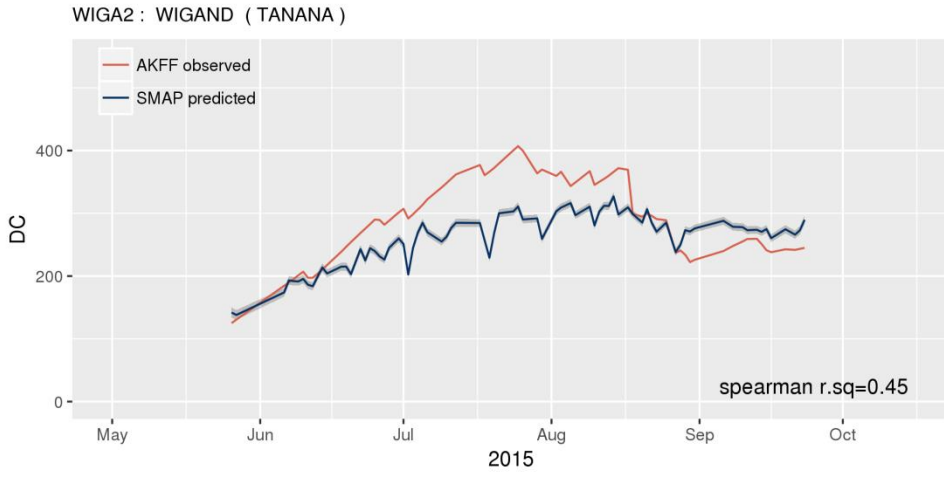


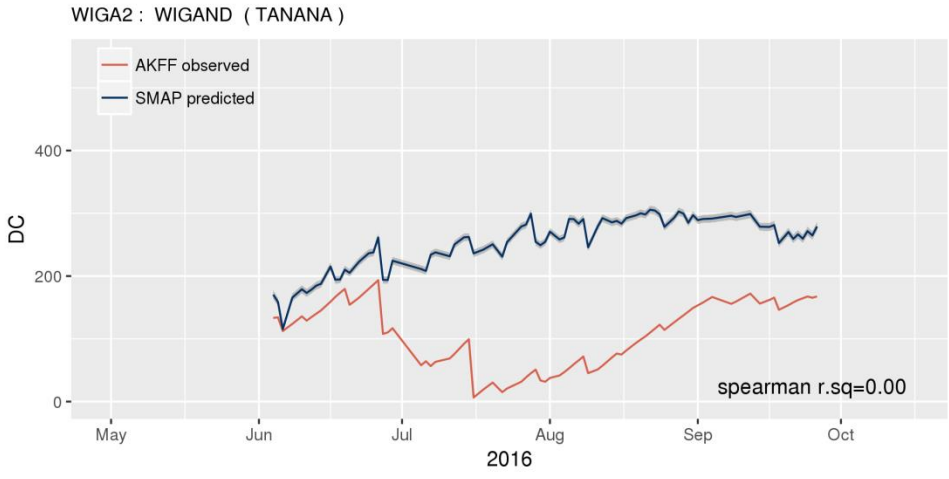
TZV : TAZLINA VILLAGE (COPPER RIVER)



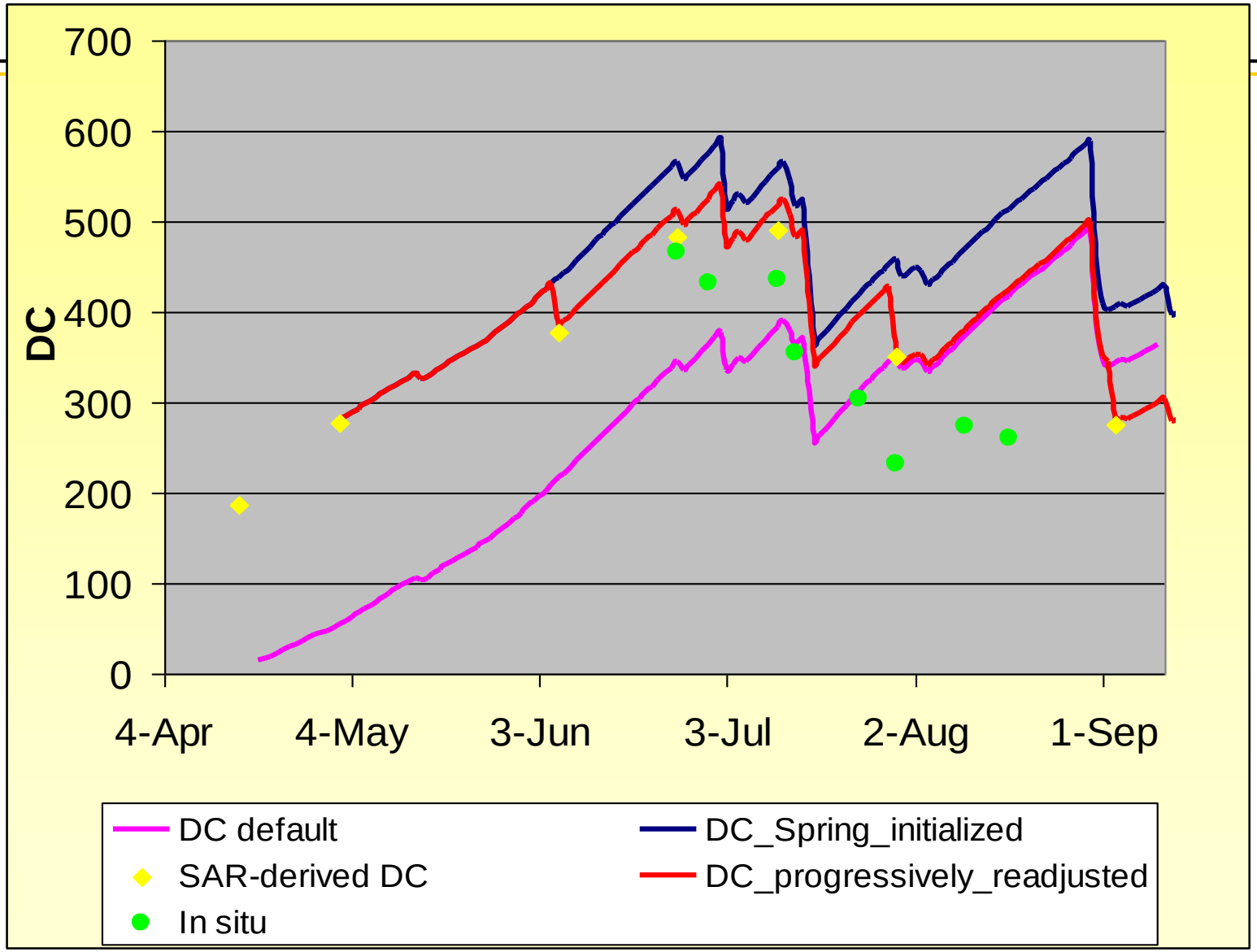

UMTA2 : UMIAT AIRFIELD (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.61


UMTA2 : UMIAT AIRFIELD (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.92


WIGA2 : WIGAND (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2015
spearman r.sq=0.45


WIGA2 : WIGAND (TANANA)
AKFF observed
SMAP predicted
DC
400
200
0
May
Jun
Jul
Aug
Sep
Oct
2016
spearman r.sq=0.00

Adjusting FWI with C-band SAR



Bourgeau-Chavez et al. 1999 IJWF, 2007 Polar Record